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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 : H04Q 7/38, G01S 5/02

A1

(11) International Publication Number: WO 00/69198

(43) International Publication Date: 16 November 2000 (16.11.00)

(21) International Application Number: PCT/CA00/00492

(22) International Filing Date: 4 May 2000 (04.05.00)

(30) Priority Data:
60/132,814 6 May 1999 (06.05.99) US

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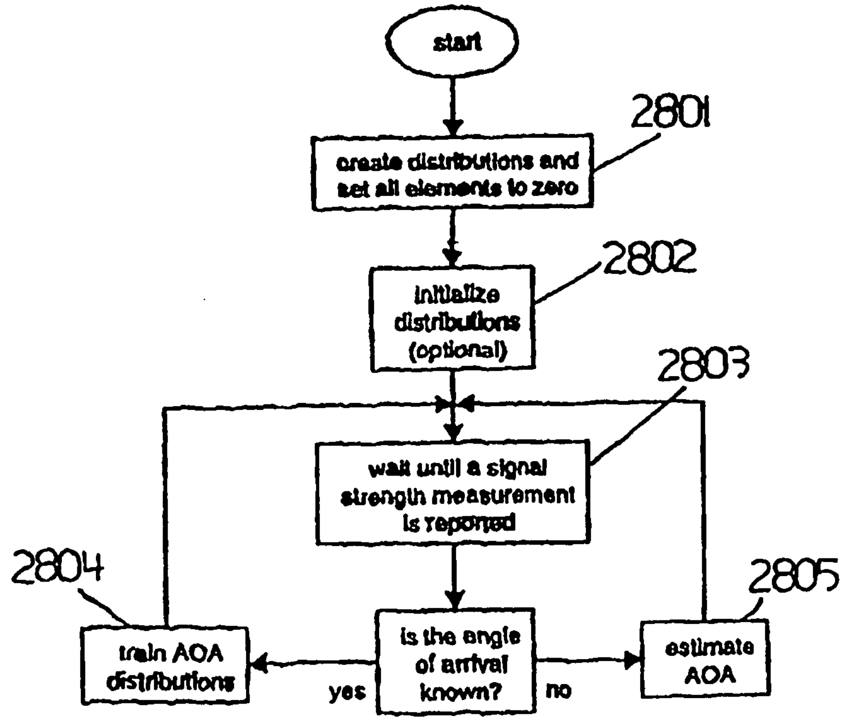
(81) Designated States: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: WIRELESS LOCATION SYSTEM

(57) Abstract

A wireless location system uses a statistical approach, in which a probability distribution is trained that relates reliable observations of a signal parameter to a known measure of location. The probability distribution is then used to locate a mobile transmitter when addition observations are available. Various precise wireless location techniques may be used to train the distribution or may be used alone to locate the mobile transmitter. In one wireless location technique, a wireless location algorithm uses weighted observations, where the observations are weighted with received signal strength.



TITLE OF THE INVENTION

Wireless Location System

FIELD OF THE INVENTION

This invention relates to methods and apparatus for locating transmitters and receivers, particularly mobile transmitters or receivers.

CROSS-REFERENCE TO OTHER APPLICATIONS

This application claims the priority of provisional application no. 60/132,814 filed May 6, 1999.

BACKGROUND OF THE INVENTION

Location of mobile transmitters has become of importance with government requirements that wireless system operators be able to locate mobile transmitters operating within their service area. The invention described herein is directed towards improved location of wireless transmitters.

The concept of estimating the angle of arrival (AOA) of radio transmissions by comparing signal strengths at two or more receiving antennas is well established. For example, U.S. patent 3,824,595 describes a system in which two receive antennas are aligned at different angles. When these antennas receive a signal transmitted from a single source, the AOA can be estimated from the strength difference of arrival (SDOA) using an AOA-SDOA relationship.

In many circumstances, it may be difficult or impractical to adequately characterize the SDOA-AOA relationship. This relationship may change due to

modification of the antennas or their position, or of objects which reflect, refract, block, or otherwise affect the transmission path from a transmitter to the receiving antennas. As well, this SDOA-AOA relationship may not be single-valued, rather, a statistical relationship may exist between SDOA and AOA.

AOA estimation is usually implemented with the objective of determining the angle at which the transmitter is located, with respect to a receiver, or Angle of Transmission (AOT). It is generally presumed that the angle of arrival (AOA) of the signal at the receiver is identical to the AOT, and hence the perceived AOA is a suitable estimate of the AOT. In some circumstances, this presumption does not hold.

One difficulty is that a signal transmitted by a mobile phone may arrive at a cellsite along a direct path, and may arrive by one or more reflected paths. The direct path arrival should always occur before the reflected arrival.

With reference to Figs. 18, 19, the AOA is estimated by measuring the signal strength at receiver A and receiver G, both equipped with directional antennas. At receiver A, the direct path is detected with lower energy than the reflected path because the antenna has lower gain in the direction of the direct path than in the direction of the reflected path. In the following, three representative cases for the signal detection are discussed. Many alternate cases, not presented here, are possible, involving blockage of the direct path, additional reflections, and failure to detect various signal arrivals.

Case 1: Suppose that AOA is estimated using the direct signal arrivals, which are the earliest signal arrivals, at receiver A and receiver G. In this case, the estimated AOA will probably be close to the AOT.

Case 2: Suppose that the AOA is estimated using the reflected signal arrivals at receiver A and receiver G. In this case, the AOA, in the strict sense, will be estimated correctly (for the reflected path). However, this angle of arrival along a reflected path is different from the AOT, and a subsequent estimate of the position of the transmitter would have significant error.

Case 3: Suppose that the AOA is estimated using the strongest signal arrivals at each antenna. In this case, the strongest signal arrival at antenna G will be the

direct path. However, the strongest signal arrival selected at antenna A is the multipath reflection. In this case, the estimated AOA or AOT would likely have significant error.

Receivers may not be capable of distinguishing between multiple arrivals and the strongest signal arrival would likely be selected by each receiver, resulting in the scenario described above in Case 3.

One obvious option is to select the earliest detected signal arrival at each individual antenna for use in AOA estimation. As the direct path will always arrive earlier than reflected paths, this approach will allow the AOT to be selected from multiple perceived AOAs in some cases. This method will fail in cases in which detection of the direct path arrival fails at any of the involved antennas.

A problem also arises in detecting transmissions from a mobile transmitter. Cohernet or non-coherent detection may be utilized. The sensitivity of coherent detection is degraded by frequency offset in the received signal. This degradation may be mitigated by executing coherent detection at multiple frequency offsets, but this solution may require prohibitive computational or hardware resources. Noncoherent detection is computationally efficient and can also be used to mitigate the effects of frequency offset, but noncoherent detection suffers from reduced sensitivity, compared to coherent detection.

While the statistical nature of the problem, and problems in detection, are difficulties encountered in location of mobile transmitters, there also exist problems related to precise location of mobile transmitters. For example, least squares methods are commonly used in the location of mobile transmitters where redundant observations of a signal parameter exist. A function that expresses closeness of location estimates, which are calculated from the observations, to an assumed location is minimized. The function is frequently the sum of squares of differences of the location estimates from a solution. The method of least squares is iterative, with modification of the solution in each iteration. If the method converges, the solution that minimized the function at the point of convergence is taken as the solution. Various problems may arise in least squares and similar iterative methods, as for

example bifucation of solutions, blunders causing grossly inaccurate location estimates and overall inaccuracy of the estimates.

SUMMARY OF THE INVENTION

This invention is intended, in its various aspects, to address the previously mentioned problems.

According to one aspect of the invention, there is provided a system for estimating the AOT and/or location of a wireless receiver. The acronym MLR (maximum likelihood region estimation) is used to refer to the method of the invention. In one aspect of the invention, multiple signals are transmitted from antennas which have differing directional gains and/or orientations and received by a receiver. The receiver unit measures a signal parameter such as the signal strength of the different transmitted signals, and these signal parametereir measurements are used to estimate the position of the receiver unit. In another aspect of the invention, multiple receivers with different antenna gain patterns receive signals transmitted from a single transmitter.

Thus, MLR can be implemented using either forward or reverse link signal measurements, or even a combination of both. The preferred embodiment of this invention is the reverse link embodiment (Reverse Link MLR), applied to an IS-95 CDMA cellular network.

Thus, according to an aspect of the invention, there is provided a method of locating a transmitter with respect to a receiver, where the transmitter is in communication with the receiver, the method comprising the steps of:

a) storing, in a database, a first set of likelihood functions, each likelihood function comprising a series of values representing the probability that a measure of location corresponds to a value of a first signal parameter, the first signal parameter being a function of a measured characteristic of signals received at the receiver;

b) receiving signals at the receiver from the transmitter;

c) estimating a value of the first signal parameter from the received signals; and

d) locating the transmitter with respect to the receiver by determining a measure of location which, by reference to the likelihood functions for the first signal parameter, corresponds to the estimated value of the first signal parameter.

In one aspect of the invention, there is provided a signal parameter estimate, for example an AOA estimate. This signal parameter estimate may be combined with other location information in order to produce an estimate of the location of the receiver in latitude and longitude, or an equivalent co-ordinate system. The other location information might be a circle defined by a round trip delay measurement, a hyperbola defined by a time difference of arrival measurement, a line defined by a separate AOA measurement, or some combination of these.

According to an implementation of the invention, the receiver relays the signal strength measurements to a device which estimates the AOT from the measurements. The device may be integrated into the receiver, lie in close proximity to the receiver, or otherwise. Preferably, every pair of signal strength measurements is used to compute an SDOA, which in turn is used to select an AOA likelihood distribution which expresses the likelihood of various AOTs, given the observed SDOA. Multiple AOA likelihood distributions may be selected, and these will be combined to yield a single AOA likelihood distribution from which the most likely AOT is selected.

In the case where one of a pair of receivers detects the signal and the other does not achieve a detection of sufficient confidence, a fixed SDOA may be assigned to that receiver pair, indicative of a much stronger SOA at the receiver which detected than the receiver which did not.

If the gain within the receiver is varied in order to maintain a desired signal levels at various intermediate stages, the variation in gain can be compensated for by scaling the digital representation of the received signal by the multiplicative inverse of the current receiver gain. In this manner, the effect of gain changes at any point in time is compensated for.

In this statistical approach, multi-valued relationships between SDOA and AOA are effectively used to estimate the AOA. For example, suppose that an observed SDOA between a particular pair of antennas of 10 dB indicates that the

AOT is equally likely to be 10 degrees or 90 degrees. Suppose that another observed SDOA indicates that the AOT is likely to be at an angle between 60 and 120 degrees. The two selected likelihood distributions are combined, yielding an AOA likelihood distribution which indicates that the AOT is about 90 degrees.

Using this statistical approach, the AOT may be correctly estimated when multipath reflections result in an AOA different from the AOT, even if the direct path is obscured. These multipath arrivals may result in multi-valued relationships between SDOA and AOA such as the example in the preceding paragraph. Suppose that an SDOA of about 10 dB is typically observed when a direct path arrives at an AOA and AOT of 10 degrees, and an SDOA of about 10 dB is also typically observed when the AOT is 90 degrees, in which case a reflected path is received. When an SDOA of 10 dB is observed, the AOA likelihood distribution corresponding to an observed SDOA of 10 dB will be selected, which will indicate that the AOT is likely 10 degrees or 90 degrees. The correct AOT can be selected by incorporating other information, such as another observed SDOA.

In addition, there are provided novel techniques for measuring and applying the relationship between SDOA and AOA, as for example by involving an empirical two-dimensional SDOA-AOA likelihood distribution.

Another advantage of the statistical approach is that the training of the SDOA-AOA likelihood distributions can be implemented using transmissions which are already available in a cellular network. For example, in an IS95 CDMA network, the mobiles will regularly report SOA measurements of pilot signals which are suitable for use in MLR training or estimation.

In a further aspect of the invention, several positioning systems are provided for making high-confidence position estimates of mobiles for use in MLR training. Alternatively, in a further aspect of the invention, conventional techniques may be used where available for providing position estimates in the training process.

To assist in avoiding multipath problems, the strongest ray for each of the received signals may be selected. The relationship between typical reflected rays and the AOT can be accounted for by the SDOA-AOA distribution, and hence the AOT

can still be accurately estimated, even though strong multipath components are included in the estimation. Alternatively, the earliest arrival may be used to attempt to avoid multipath problems.

IS-95 CDMA provides a separate pilot signal from each sector of a cellsite. In a further aspect of the invention, the distinct pilot signals can be used as the multiple received signals for MLR. The strengths of these signals can be measured by an IS-95 CDMA mobile phone.

In one aspect of the invention, MLR collects multiple observations of signal strength of arrival at known angles of arrival in order to create empirical likelihood distributions (analogous to theoretical probability distribution functions) of SDOA and AOA, which are in turn used to predict the AOA for subsequent SDOA observations.

In another aspect of the invention, non-detection or failure to detect a signal is incorporated into the AOA information. For example, suppose that mobiles at azimuths of 10° to 30° relative to a cellsite are highly likely to detect the Sector A pilot signal and to not detect the Sector B pilot signal, and furthermore suppose that this situation is unlikely to occur at other azimuths. As the distribution for Sectors A and B is trained over time, the elements having bins valued high_SDOA_bin at azimuths from 10° to 30° will have values much larger than other bins from 10° to 30° azimuth. Whenever a mobile at unknown azimuth reports detection of the Sector A pilot and not the Sector B pilot, the distribution will indicate a high probability that the mobile is at an azimuth between 10° and 30°.

One object of the invention is to estimate the location of a transmitting device. Alternatively, MLR may be used to resolve multiple location solutions or validate a location estimate from TDOA, AOA or other means. As well, MLR can be used in order to select between a number of probable locations for a transmitting device. Additional uses of MLR include generating wireless coverage maps, and wireless capacity and coverage analysis and planning.

The preferred embodiment utilizes SDOA observations taken from pairs of receiver SOA observations, rather than using SOA observations directly. In the

preferred and other embodiments, the transmit power of the transmitter can vary considerably and is difficult to predict. The use of SDOA obviates the need to determine the transmitted power.

In a further aspect of the invention, within the network area, there are a number of receivers which report SOA measurements of received transmissions to the MLR Host. The Host maintains an SDOA likelihood distribution, a means for training the likelihood distribution, and a means for using the likelihood distribution to estimate location.

In a further aspect of the invention, a secondary search method is used to enhance detection of a transmission by receivers. When a receiver reports detection of a transmission to the Host, the Host may order other receivers to conduct an enhanced search for said transmission. All receivers which detect the transmission report the observed SOA to the Host.

In an aspect of the invention, the Host then attempts to determine the location of the transmitter by means other than MLR. If this is successful then the Host trains the MLR distribution by incrementing the distribution elements corresponding to the all pairings of observed SOAs, and the known location.

In an aspect of the invention, if the Host is unable to determine the location of the transmitter by means other than MLR, then the Host proceeds to estimate the location by MLR. The Host extracts from its overall MLR distribution one or more (x,y) likelihood distributions which correspond to the observed SDOAs. These distributions are combined into a single (x,y) likelihood distribution from which the location is estimated.

In an aspect of the invention, if one of a pair of receivers reported successful detection and the other did not, then an observed SDOA can still be computed in which the SOA of the non-detecting receiver is assumed to be a number less than the smallest realizable SOA. In order to suppress the processing of SDOAs which offer negligible improvement to training or estimation, the assignment of the very low SOA to a non-detecting receiver is suppressed if there has been no previous occurrence of detection of a transmission by both receivers.

The various aspects of this invention afford a number of advantages over the prior art. These advantages include the ability of the invention to self-train using transmissions which are already present, without requiring dedicated equipment or effort. A related advantage is the capability of the invention to add to the training information over time in order to adapt to changing propagation conditions.

Another advantage of an aspect of this invention is the ability to incorporate observations from an arbitrary number of receivers in order to make the best estimate possible of transmitter location. When a receiver is added or removed from the set of receivers, the adaptive training can incorporate this change and maintain near-optimal usage of current and new training data.

Yet another advantage of an aspect of this invention is the ability to use non-detection information to assist in estimating the location of a transmitter. For example, if a transmission is detected by only one receiver, and training data indicates that a transmission detected by said receiver alone and not by the neighboring receivers has a high likelihood of originating from a particular area, then MLR will yield a point in said area as a location estimate for the transmitter.

Yet another advantage of an aspect of this invention is the capability to learn and recognize non single-valued path losses within region. For example, if transmissions from a particular region exhibit an SDOA which has a multimodal (2 or more peaks) likelihood distribution, the invention will not distort the observations by transforming them to a single average path loss (as would a signal strength contour map) nor to transforming them to a single average path loss with a large variance. By storing the observed likelihood distribution, the invention preserves all higher-order statistics of the observed SDOAs.

Yet another advantage of an aspect of this invention is applicability (as Forward Link MLR and/or Reverse Link MLR) to many types of wireless systems and transmission formats. All, some, or none of the receivers may be co-located with other wireless infrastructure such as cellular towers. Many wireless systems already incorporate signals and measurements which are usable as receiver SOA observations. For example, in IS-136 TDMA cellular and GSM cellular, the mobile

units monitor and report on the SOA of control channel signals from multiple base station sectors. In AMPS cellular, base stations in the vicinity of a mobile monitor and report on the SOA of mobile transmissions.

Yet another advantage of an aspect of this invention is the ability to incorporate multiple types of measurements into the training of and estimation using likelihood distributions. Phase difference of arrival information is as readily represented in lieu of or along with SDOA information, as is TDOA, and any other signal characteristic which can have any relation, directly or indirectly, to the positions and orientations of transmitter and receivers.

Yet another advantage of an aspect of this invention is the ability to incorporate myriad forms of location relevant information. Position information provided by a network-based TDOA system or from GPS system can readily be incorporated as training data. If such a TDOA or GPS system, or an AOA system, is able to resolve the transmitter location to a locus (such as a hyperbola), this may be superimposed with an MLR likelihood distribution in order to select the location which best satisfies all available observations.

In further aspects of this invention, there are provided non-statistical methods of locating a mobile transmitter, and in particular a CDMA transmitter, with precision, which may be used to train the MLR method of locating a mobile transmitter or may be used alone. These non-statistical methods are outlined in the following aspects of the invention.

According to a further aspect of the invention, there is provided a network-based Wireless Location System (WLS) whereby existing CDMA CTs can be located passively without modification to the CT or to the cellular antenna infrastructure.

According to a further aspect of the invention, there is provided a method of estimating the static and kinematic positional information of a CDMA CT which transmits a signal, $s(t)$ by monitoring the corresponding received signal $r_{i,k}(t)$ at the k^{th} antenna of the i^{th} MS.

According to a further aspect of the invention, there is provided a method of correcting for the sources of error that affect the different location technologies for an

IS-95 CT in a unique and novel way, including frequency errors, clock offsets, overall group delays, multipath and interference, while minimizing the effect of noise and reducing HDOP (Horizontal Dilution of Precision).

According to a further aspect of the invention, there is provided a method of locating a powered-up IS-95 CT in a passive manner by using the signal transmitted by the CT over the Access channel or the Reverse Traffic channel. In order for the CT to be truly passive, it is possible to turn its ringer off, and request the BS to page it (e.g. by calling the CT from the HOST or by other means).

According to a further aspect of the invention, there is disclosed the use of an Access message for locating the CT by processing the signal representation of the message by the MS or associated equipment, without transferring the complete signal representation of the received Access message to the host.

According to a further aspect of the invention, there is provided a method of locating a powered-up IS-95 CT by using the signal transmitted by the CT over the Reverse Traffic channel without incurring air time charges and while the CT remains in the "waiting for answer" mode.

According to a further aspect of the invention, there is provided a method of locating an IS-95 CT by estimating the Phase of Arrival (POA) of existing or generated tones either over the Access channel or the Reverse Traffic channel. The phases can be extracted using SR algorithms in order to reduce the effect of multipath.

Preferably, the overall group delay variations through the receiver at each MS caused by the effect of temperature, interference and aging in the receiver are reduced by replacing some analog RF components by digital components. Preferably, the effect of Local Oscillator (LO) drift and clock offsets is reduced by using the Global Positioning System (GPS) as a source for a common reference.

According to a further aspect of the invention, there is provided a method of locating a 911 Cellular caller and to transfer its positional information to the appropriate PSAP during "unanswered conversation" mode.

According to a further aspect of the invention, there is provided a method of locating a mobile transmitter in which the observations of the received signal at a receiver are weighted in the wireless location algorithm, such as an iterative minimizing algorithm, according to the received signal strength of the received signals. It is desirable to minimize HDOP by allowing more MSs to tune to the same CT while at the same time reducing the effect of noise and multipath by solving for the position of the CT using Least Squares weighted by RSSI.

According to a further aspect of the invention, there is provided a method of locating a mobile transmitter using an iterative algorithm in which misclosures and standardized residuals are used to flag the observations that might have a blunder.

According to a further aspect of the invention, there is provided Chaffee's method or Location On the Conic Axis (LOCA) is used to detect solution bifurcation in an iterative minimizing function. LOCA and/or Plane Intersection may be used to provide an initial position for the iterative minimizing function, such as by using Least Squares.

TDOA observations, hybrid TDOA observations and AOA observations may be used to locate the CT. TDOA information from two MSs or the AOA from several antennas at the same MS may be used to resolve the AOA ambiguity at such an MS. Range information from two MSs or the AOA from several antennas at the same MS may be used to resolve the AOA ambiguity at such an MS.

In hybrid TDOA, a transmitter is located by TDOA in which TDOA observations are calculated by subtracting the TOA of the received signal at a selected one the receiving sites from the TOA at all other receiving sites.

In a further aspect of the invention, grouped coherent detection of a mobile transmission is used to achieve near coherent detection accuracy, with less complexity. In a further aspect of the invention, an improved method of noncoherent detection is proposed in which the subcorrelations are low pass filtered (with a cutoff frequency of approximately the largest expected doppler frequency) before combining. Alternatively, the subcorrelations are passed through a set of filter banks, whose passbands collectively cover the range of expected doppler frequencies.

Computer readable media containing instructions to a computer or signal processor for carrying out the methods (algorithms) described here are also claimed, as well as apparatus such as a computer or signal processor programmed or hardwired to carry out the methods described here.

These and other aspects of the invention are described in the detailed description of the invention and claimed in the claims that follow.

BRIEF DESCRIPTION OF THE DRAWINGS

There will now be described preferred embodiments of the invention, with reference to the drawings, by way of illustration only and not with the intention of limiting the scope of the invention, in which like numerals denote like elements and in which:

Fig. 1 illustrates transmission by a CT (101) of a signal s(t) (103)to a base station.

Fig. 2 illustrates the transmission of the signal s(t) by the CT at **Time 'τ_0'** and its reception by the k^{th} antenna at the i^{th} Monitoring Site (MS) (201) at **Time of Arrival: $\tau_{i,k}$**

Fig. 3 illustrates a three MS system which receives a signal transmitted from a Cellular Telephone (CT) located at (x,y).

Figure 4 illustrates the **Direction of Travel (DOT)** **'φ'** (401) relative to Northing (in a clockwise manner from Northing) and the **speed v** (402) of the CT (404) of coordinates (x,y) which together represent the velocity $\bar{\mathbf{v}}$ of the CT.

Fig. 5 illustrates a possible Angle of Arrival (AOA) likelihood function, given a particular Phase of Arrival (POA) difference between two antennas. The graph has two peaks, at 30° and 150°. This indicates that when a certain difference in phase of arrival of a CT transmission is observed at the two antennas, it is likely that the angle of arrival of the CT transmission at the antennas is either 30° or 150°.

Figure 6 illustrates the two intersecting **loci of Position** for the two-dimensional (horizontal) coordinates (x,y) of the CT (603) based on $TDOA_{2,1,k,m}$ (601) and $TDOA_{3,1,n,m}$ (602). In other words, it is possible to solve for (x,y) as the

intersection between the two trajectories obtained using three Times of Arrival (TOAs) (after choosing the correct side of each hyperbola). In order to solve for (x,y,z) we require four TOAs.

Figure 7 illustrates a **Second Stage** of a wireless location system where the i^{th} MS down-loads its positional information to a central processor which we refer to as the **Host** (701). The Host uses all the positional information to estimate the coordinates **(x,y)** of the CT and its speed **v** and DOT φ. In the discussion of Fig. 7, it is assumed that each MS has two antennas placed on the same horizontal plane.

Figure 8 illustrates the description of an exemplary design, referred to here as **Design I,** for the IF-sampling receiver.

Figures 9a, 9b, 9c and 9d illustrate a flow diagram for a TDOA positioning strategy used for reliable position measurement. The positioning strategy consists of a number of algorithms (Least Squares, Location On the Conic Axis (LOCA), Plane Intersection) and numerous decisions. Given a set of observations, there are 4 possible outcomes: two LS position solutions (908), two LOCA position solutions (909), one LS position solution (923, 936), and no position solution (927).

Fig. 10 illustrates a possible AOA likelihood function, given a particular Strength of Arrival (SOA) difference between two antennas. The graph has a wide peak, from approximately 0° to 45°. This indicates that when a certain difference in SOA of a CT transmission is observed at the two antennas, it is likely that the angle of arrival of the CT transmission at the antennas is between 0° and 45°.

Fig. 11 illustrates a second possible AOA likelihood function.

Fig. 12 illustrates one implementation of an algorithm for Maximum Likelihood Angle of Arrival (ML-AOA) estimation.

Figs. 13 and 13A are flow diagrams illustrating implementation of an algorithm for detecting CT transmissions.

Fig. 14 illustrates an exemplary embodiment of a monitoring site and Host.

Figure 15 illustrates a 2-D representation of a MS with three antennas positioned on the corners of an equilateral triangle. Figure 15 assumes, without loss of generality, that the three antennas belong to the same horizontal plane as well as a

CT. Each antenna receives a signal transmitted from the CT. Such a structure is typical of a three sector CDMA cellular and PCS infrastructure.

Figure 16a plots the PDOA (Phase Difference of Arrival) between antennas 1 and 2, shown in Figure 15, with respect to the AOA of the signal transmitted by the CT with respect to the line formed by joining $antenna_1$ to $antenna_2$, clockwise.

Figure 16b plots the PDOA between $antenna_2$ and $antenna_3$, shown in Figure 15, with respect to the AOA of the signal transmitted by the CT with respect to the line formed by joining $antenna_1$ to $antenna_2$, clockwise.

Figure 16c plots the PDOA between $antenna_3$ and $antenna_1$, shown in Figure 15, with respect to the AOA of the signal transmitted by the CT with respect to the line formed by joining $antenna_1$ to $antenna_2$, clockwise.

Figures 16a, b and c assume, without loss of generality, that the baseline between any two antennas (shown as $d_{i,1,2}$ in Figure 15) is 2/3 meters and that the wavelength of the signal transmitted from the CT corresponds to a carrier frequency of 1.9GHz. Figures 16a, b and c also assume that the CT is far from all antennas with respect to their baseline, $d_{i,1,2}$.

Figure 17 illustrates a 2-D (vertical) representation of a MS with two antennas separated in the z-axis, i.e. of different elevation. Figure 17 assumes, without loss of generality, that the two antennas are placed on the same vertical axis and that the CT is placed on the same vertical plane as the vertical axis. Each antenna receives a signal transmitted from a Cellular Telephone (CT) with a given elevation angle. The elevation angle between a CT and a given antenna is defined as the angle between the horizontal plane of the CT and the line joining the CT and the antenna. Such a structure is typical of a vertical diversity cellular or PCS system.

Fig. 18 shows typical orientations of sectors at a sectorized cellsite, and illustrates the angle of arrival. Note that although the receiver will in theory receiver signals from all three transmitters, if the transmission antenna patterns are typical of a sectorized cellsite (as in Fig. 17), transmitter A will be received at a lower strength than transmitter G, and transmitter B will be received at an even lower strength, possibly so low that the receiver cannot detect it.

Fig. 19 shows typical antenna gain patterns for cellsite with three sectors.

Figs. 20a and 20b shows the relationships between the strength of the pilot signals of sectors A and B, and the angle of arrival. Note that the relationship shown is idealized, in that actual field measurements would exhibit significant variation in strength versus time and versus angle.

Fig. 21 shows the relationship between the difference in the strengths of pilots A and B, as measured by the mobile, versus the angle of arrival. The relationship shown in idealized.

Fig. 22 illustrates multiple signal arrivals arising from the direct path and a multipath reflection.

Fig. 23 shows a correlator output which might be generated as a result of multiple signal arrivals.

Figs. 24a, 24b and 24c illustrate the effect of combining two AOA likelihood distributions to produce a single, composite likelihood distribution.

Fig. 25 illustrates the structure and interpretation of a an SDOA-AOA distribution, implemented as a two-dimensional array of numbers, which represents a two-dimensional likelihood distribution of strength difference of arrival and angle of arrival.

Fig. 26 shows a single element of an SDOA-AOA distribution. Such an element corresponds to the following defining parameters:

N_SDOA_bins = 41,
low_SDOA_bin = -20 dB,
high_SDOA_bin = 20 dB, and
N_AOA_bins = 361.

The bin values for SDOA and AOA, 2 dB and 56°, and the region associated with the distribution element, are shown. As well, two SDOA-AOA points are shown, one within the region and one outside of the region of the element.

Fig. 27 illustrates the azimuth initialization of the SDOA-AOA distribution for a pair of antennas having azimuths at 120° and 240°. Note that the plot should be

interpreted as being periodic with respect to angle of arrival, so that the plot shows two line segments: one labeled "front side", and another labeled "back side". The two parts shown labeled "back side" are parts of the same line segment.

Fig. 28 illustrates an embodiment of the overall procedure for ML-AOA operation including initialization, training, and estimation.

Fig. 29 illustrates SDOA values for a pair of receivers. Each number shown indicates the SDOA value that might be observed when the transmitter is at the position of the number, and the SDOA is computed as the difference (SOA of receiver 1) - (SOA of receiver 2).

Fig. 30 shows the main physical elements of an exemplary embodiment of the MLR system. A number of receivers detected a transmission from the transmitter and report measurements to the MLR Host.

Fig. 31 illustrates the secondary search process. The secondary search focuses effort on searching for a transmission detected by the primary search.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

In this patent document, the word "comprising" is used in its non-limiting sense to mean that items following the word in the sentence are included and that items not specifically mentioned are not necessarily excluded. The use of the indefinite article "a" in the claims before an element means that one of the elements is specified. but does not specifically exclude others of the elements being present, unless the context clearly requires that there be one and only one of the elements. In the detailed description of the invention, there are several aspects of the invention disclosed. Wherever "the intention of the invention" or "intention of the patent" is referred to, this means that the following item is an invention of an aspect of one of the inventions and not necessarily the intention of all the inventions or the intention of all aspects on one or more inventions. Further, where an invention is said to "consist of" something in the detailed description, this particular aspect of the invention incorporates the mentioned steps or their equivalents, but this is not intended to limit a claim to the same feature. Where an element or step is said to be crucial (or like words), this refers to the element or step

being crucial to the particular aspect of the invention being discussed, and may not be crucial to other aspects of the invention. Where the invention is said to "intend" to do something for a purpose, then this means that, for the particular purpose stated, it is preferred to do that thing in the carrying out of the invention. A "bin" is a counting mechanism, such as an element in a memory device, with a value or count that may be incremented under instruction from a microprocessor. A wireless location algorithm is any algorithm that may be used to locate a wireless transmitter, and includes the algorithms described in this patent document.

The following definitions take precedence over definitions for the same terms that can be found in the open literature.

Cellular Telephone (CT): is a device, which can be portable or fixed, that can consist of a transmitter alone, or both a transmitter and a receiver. It can be a regular Cellular Telephone (CT), a PCS (Personal Communication Systems) telephone, a cordless telephone, a Personal Digital Assistant (PDA), a GPS receiver, or a combination thereof. It can be a radio tag or a wireless telephone that does not contain the audio portion of the telephone. It can also be a transmitter that transmits periodically over a given channel, or a receiver that receives Radio signals, or both.

Mobile Receiver (MR): is a device, which can be portable or fixed, that can consist of a receiver alone or both a receiver and a transmitter. It can be a regular Cellular Telephone (CT), a PCS (Personal Communication Systems) telephone, a cordless telephone, a Personal Digital Assistant (PDA), a GPS receiver, or a combination thereof. It can be a radio tag or a wireless telephone that does not contain the audio portion of the telephone. It can also be a transmitter that transmits periodically over a given channel, or a receiver that receives Radio signals, or both.

Base Station (BS): is a device of known location with respect to other BSs at a given time. A BS can be portable or fixed. It can consist of a transmitter alone or a receiver or both. It can be a regular cellular Base Station, a regular satellite transceiver, a PCS Base Station, an ESMR Base Station, a Paging Base Station or any other type of transmitter/transceiver combination. Most cellular/PCS BSs use some form of

diversity antennas: vertical (i.e. the antennas are separated vertically), horizontal (i.e. the antennas are separated horizontally) or both.

Cell: is a geographical area serviced by a cellular Base Station (BS).

Sectorized cell: is a cell that is made of multiple spatially differentiated sectors. Each sector can be considered as an independent cell to be serviced by an independent cellular BS. However, sectors in a cell are usually serviced by the same cellular BS in order to minimize cost and complexity. We refer to such a BS as a **sectorized BS**. Antennas belonging to a sectorized BS are usually, but not necessarily, placed on the same horizontal plane.

Sector antennas: are directional cellular antennas which are used by a BS to transmit and receive over spatially differentiated regions. Each sector has a dedicated antenna (or set of antennas if diversity is applied).

Diversity Antennas: are cellular antennas which provide redundant reverse-link signals to a BS. Diversity can be accomplished by means including multiple antennas separated horizontally or vertically, or with different polarizations. In this patent, we use horizontally separated diversity antennas as a mean to estimate the horizontal Angle Of Arrival (AOA) of the received radio signal at a MS. When the diversity antennas are vertically separated, either the elevation AOA is estimated, or the received signals from all antennas at a given MS is combined using: selection combining, maximal ratio combining, co-phasing combining, equal gain combining, or other methods of combining.

Estimating the horizontal AOA of the received radio signal at a MS can be used to estimate the range between the CT and the MS as long as the altitude of the CT is known.

Monitoring Site (MS): is a receiver that has the ability to monitor all four channels: Access, Paging, Forward Traffic, and Reverse Traffic. It is appropriate to collocate the MS with the BS in order to take advantage of the existing cellular infrastructure. The patent however does not require such a collocation since the MS performs all

reception tasks independent of a BS. In fact, the MSs can be mobile as long as their estimated location is known in time.

Host: is a central processor to process all positional information that are received from the MSs and to transmit monitoring orders to all MSs. The host can also be responsible for location services such as fleet management, location sensitive billing, etc. The Host can also be responsible for software/firmware upgrades/re-configurations of the MSs.

Access Channel: is the channel to be used by the CT to transmit control signals to the BS such as call originations, registrations, etc. This channel is analogous to the Reverse Control Channel in AMPS.

Paging Channel: is the channel used by the BS to transmit control messages to the CT such as paging the CT, acknowledging a registration, etc.

Reverse Traffic Channel is the channel assigned by the BS to the CT, which the CT uses to transmit voice data, messages, and other data to the BS, during a CDMA call.

Forward Traffic Channel: is the channel assigned by the BS to the CT on which the BS will transmit voice data, messages, or other data to the CT during a CDMA call.

Pilot Channel: is the channel on which the BS broadcasts the pilot signal, which is used by the CT for detection of the BS, synchronization, and RSSI estimation.

Sync Channel: is the channel on which the BS broadcasts the Synchronization Message, which is used by the CT for synchronization of its internal timing and states, and for configuration of some network-dependent parameters.

Originations: are defined as calls initiated by a CT.

Pages: are initiated by a BS to a CT.

Reverse Traffic Mode: A step in the establishment of a call is for the CT to enter the Reverse Traffic Mode, in which the CT begins to transmit on the Reverse Traffic channel. The mobile enters this mode after the mobile has acquired (begun to receive) transmissions on the Forward Traffic channel. This is analogous to the Reverse voice channel in AMPs.

Unanswered conversation mode: is defined as an origination that is in conversation mode that has not been answered yet by the called party.

Answered conversation mode: is defined as an origination that is in conversation mode that has been answered by the called party.

Super-Resolution (SR) Algorithm: is an operation that transforms a time domain signal, s(t), to a frequency domain signal, S(f), in such a way that the frequency domain signal, S(f), has a better resolution than the resolution offered by the Fourier transform, i.e. S(f) has a better resolution than the Fourier transform F{s(t)}, of s(t). Vice-versa, a SR algorithm transforms a frequency domain signal, S(f), to a time domain signal, s(t), with a better resolution than the resolution offered by the inverse Fourier transform, i.e. s(t) has a better resolution than the inverse Fourier transform $F^{-1}\{S(f)\}$, of S(f)). Examples of SR algorithms are well known in the literature and include: MUSIC/Root MUSIC, ESPRIT,

Auto Regressive Moving Average, Minimum Variance, MUSIC using Higher Order Statistics, ESPRIT using Higher Order Statistics. Auto Regressive Moving Average using Higher Order Statistics, or Minimum Variance using Higher Order Statistics.

Frequency-domain Rayleigh Resolution: is the frequency-domain resolution offered by the Fourier transform.

Time-domain Rayleigh Resolution: is the time-domain resolution offered by the inverse Fourier transform.

Inverse SR algorithm: is an algorithm which processes a time domain signal in order to improve its time-domain resolution over the conventional time-domain Rayleigh resolution. A preferred embodiment of the inverse SR algorithm comprises a conventional time domain correlator, a time domain window, a Fourier Transform, a frequency domain window, a frequency domain equalizer, and a processor which performs a SR algorithm in order to resolve the TOAs in the received signal at a given MR. Alternatively, an inverse SR algorithm can process a frequency domain signal in order to improve its frequency-domain resolution over the conventional frequency-domain Rayleigh resolution. In this case, a preferred embodiment of the inverse SR algorithm comprises a frequency domain correlator, a frequency domain window, an inverse Fourier Transform, a time domain window, a time domain

equalizer, and a processor which performs a SR algorithm in order to resolve the FOAs in the received signal at a given MR.

Fourier Transform-Based Filters: are filters that: Fourier Transform the time domain signal, then window the transformed signal over a given band, and Inverse Fourier Transform the windowed signal.

Effective Bandwidth: is the bandwidth over which the received radio signal at a given MS has been observed during a given observation interval.

Passive Location of a CT: is the location of a CT without its bearer's knowledge.

Surface Wave Propagation: is the propagation of the Radio waves that follow the surface of the earth. Such a propagation might have a different velocity than free-space propagation.

Elevation Angle: between a CT and a given antenna is defined as the angle between the horizontal plane of the CT and the line joining the CT to the antenna.

Angle of Arrival (AOA) - the angle or direction from which a transmission arrives at a receiver. Except where otherwise stated in this document, the AOA and AOT are assumed to be identical.

Angle of Transmitter (AOT) - the angle or direction at which a transmitter or group of transmitters is located with respect to a receiver. Note that the AOA and AOT are identical in many, but not all cases.

Cellsite - A location of multiple wireless transmitters. In the preferred embodiment of this invention, the transmitters consist of sectors of a cellsite in a cellular communications network, however, this invention may be implemented using any type of transmitters.

Azimuth - a representation of angle measured in degrees clockwise from due North.

Transmitter - A device which transmits wireless signals, such as a cellular phone. This may include elements such as a power supply, electronic oscillator circuits, modulation circuits, amplifiers, and one or more antennas. A transmitter may include an integrated receiver, as is the case with a cellular phone, or it may be a transmit-only device.

__Network Area__ - A general region in which there are receivers. and within which the locations of certain transmitters can be estimated by MLR. The network area could be the interior of a building, a city, a continent, or a region of space near or far from the surface of the Earth.

__Receiver__ - A device which is capable of receiving transmissions from one or more transmitters, and of measuring the received signal strength or strength of arrival (SOA) of the signal. A receiver typically consists an antenna, a radio frequency downconverter, and signal processing circuitry.

Universal Transverse Mercator (UTM) Grid System - A co-ordinate system for identifying locations on the surface of the Earth. There are 60 UTM zones defined by lines of longitude at 3 degree intervals. A position within a zone is defined by the distance north from the Equator ("northing"), and the distance east from a north-south reference line ("easting").

Strength of Arrival (SOA) - The amplitude or power of a signal arriving at a receiver.

Strength Difference of Arrival (SDOA) - The difference between the strengths of arrival of one signal at two difference receivers, or the difference between the strengths of arrival of two signals at one receiver.

dBm - A logarithmic measure of signal power, obtained by multiplying the logarithm of power in milliwatts by 10.

The principles of locating a mobile transmitter, eg a CT, using AOA are illustrated in Figs. 1-4.

Fig. 1 illustrates transmission by a CT (101) of a signal s(t) (103). When the CT is IS95-based, it transmits a signal either over the Access channel or over the Reverse Traffic channel. In either case, the transmission is intended for a specific Base Station (BS) (102). Fig. 1 assumes that the BS (102) has two antennas that belong to the same horizontal plane.

Fig. 2 illustrates the transmission of the signal s(t) by the CT at **Time 'τ_0'** and its reception by the k^{th} antenna at the i^{th} Monitoring Site (MS) (201) at **Time of Arrival:** $\tau_{i,k}$. In order to solve for the horizontal coordinates (x,y) of the CT (202), a

minimum of three MSs (with a minimum of one antenna per MS) are required using TDOA positioning, or a minimum of two MSs (with a minimum of two horizontally spaced antennas per MS) using Angle Of Arrival (AOA) positioning. In either case, it is possible to take advantage of the cellular infrastructure by locating the MSs at the BS sites, thereby using their:

1. directional antennas (either diversity or sectored) with good RF coverage and appropriate RF front end,

2. high speed link to the Mobile Switching Center (MSC) using either a T1-Link or a wired telephone link (Plain Old Telephones (POTs)), and

3. convenient weather-proof temperature-regulated housing with regulated power supply.

It is however possible to place the MSs at locations that are independent from the cellular BSs since the method of the invention does not require any assistance from the BSs or from the MSC. In Fig. 2, each MS (201) has two antennas.

Fig. 3 illustrates a three MS system which receives a signal transmitted from a Cellular Telephone (CT) located at (x,y). In Fig. 3 each MS has two antennas placed essentially on the same horizontal plane. In Fig. 3, when the CT is far from each MS with respect to the baseline between the two antennas at each MS, the received wavefront is planar i.e. $\gamma_{i,1} \cong \gamma_{i,2} \cong \gamma_i$, where:

- $\gamma_{i,1}$ is the Angle Of Arrival (**AOA**), at the first antenna of the i^{th} MS,
- $\gamma_{i,2}$ is the AOA at the second antenna of the i^{th} MS, and
- γ_i is defined as the angle formed between:

  1. the line joining the CT (301) and the i^{th} MS (which we refer to as $\mathbf{line}_{1,i}$) and,

  2. the line joining the two antennas at the i^{th} MS (which we refer to as $\mathbf{line}_{2,i}$);

in a clockwise manner from $\mathbf{line}_{1,i}$ to $\mathbf{line}_{2,i}$, where i=1, 2, 3. In Fig. 3, $\mathbf{line}_{1,i}$ and $\mathbf{line}_{2,i}$, for i=1, 2, 3, are all on the same horizontal plane, when the elevation of each antenna is much smaller than the distance between the antenna and the CT.

Fig. 4 illustrates the **Direction of Travel (DOT)** 'φ' (401) relative to Northing (in a clockwise manner from Northing) and the **speed** v (402) of the CT (404) of coordinates (x,y) which together represent the velocity $\bar{v}$ of the CT. The k^{th} antenna at the i^{th} MS (403) of coordinates $(x_{i,k},y_{i,k},z_{i,k})$ receives the signal $r_{i,k}(t)$, processes it and transfers the positional information regarding the CT to a central processor, where i=1, 2, 3. In Fig. 4, each MS may have two antennas placed on the same horizontal plane and the CT and all antennas are also placed on effectively the same horizontal plane.

Figure 5 illustrates the two-dimensional (horizontal) **Locus of Position** (501) for $TDOA_{2,1,k,m}$ which is defined as

$$\begin{aligned} TDOA_{2,1,k,m} &= \tau_{2,k} - \tau_{1,m} \\ &= (\tau_{2,k} - \tau_o) - (\tau_{1,m} - \tau_o) \\ &= \frac{1}{c}\sqrt{(x_{2,k} - x)^2 + (y_{2,k} - y)^2} - \frac{1}{c}\sqrt{(x_{1,m} - x)^2 + (y_{1,m} - y)^2} \end{aligned}$$

(1)

where c is the speed of propagation, $(x_{1,m}, y_{1,m}, z_{1,m})$ are the coordinates of the m^{th} antenna at MS_1, $(x_{2,k}, y_{2,k}, z_{2,k})$ are the coordinates of the k^{th} antenna at MS_2, and (x,y) are the coordinates of the CT (502). This is achieved using Time Difference of Arrival (TDOA)-based Hyperbolic Multi-lateration (as shown in Turin, G. L. et al., "A Statistical Model of Urban Multipath Propagation," *IEEE Transactions on Vehicular Technology*, Vol. VT-21, No. 1, February 1972, and as shown in Smith, J.O. et al., "Closed-Form Least-Squares Source Location Estimation from Range-Difference Measurements," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. ASSP-35, No. 12, December, 1987). In the case where the three-dimensional coordinates of the CT are required, we have to solve for (x,y,z) using

$$\begin{aligned} TDOA_{2,1,k,m} &= \tau_{2,k} - \tau_{1,m} \\ &= (\tau_{2,k} - \tau_o) - (\tau_{1,m} - \tau_o) \\ &= \frac{1}{c}\sqrt{(x_{2,k} - x)^2 + (y_{2,k} - y)^2 + (z_{2,k} - z)^2} \\ &\quad - \frac{1}{c}\sqrt{(x_{1,m} - x)^2 + (y_{1,m} - y)^2 + (z_{1,m} - z)^2} \end{aligned} \tag{2}$$

Figure 8 illustrates the description of **Design I (discussed below)** for an exemplary IF-sampling receiver for use in locating a mobile transmitter with precision, and which may then be used in training the MLR process. The received RF signal $r_{i,k}(t)$ at the k^{th} antenna of the i^{th} MS is initially filtered by an RF Band Pass Filter (BPF) (802), amplified by an RF amplifier (803), and down-converted to the Intermediate Frequency (IF) by a Mixer (805). The IF signal is amplified by an IF Amplifier (806), filtered by a Band Pass Filter (807), amplified by an IF Amplifier (808) to form the IF output. The IF output is sampled by an A/D (809) and then processed by a Digital Signal Processor (810). A Frequency Reference signal (811) is provided to the RF synthesizer. A preferred source for the reference signal is one that is common to all MSs such as a Global Positioning Systems (GPS) signal, or one that is derived therefrom.

In Fig. 10, the graph has two peaks, at 30° and 150°. This indicates that when a certain difference in phase of arrival of a CT transmission is observed at the two antennas, it is likely that the angle of arrival of the CT transmission at the antennas is either 30° or 150°.

Fig. 11 illustrates a possible AOA likelihood function, given a particular Strength of Arrival (SOA) difference between two antennas. The graph has a wide peak, from approximately 0° to 45°. This indicates that when a certain difference in SOA of a CT transmission is observed at the two antennas, it is likely that the angle of arrival of the CT transmission at the antennas is between 0° and 45°.

Figure 12 illustrates one implementation of an algorithm for Maximum Likelihood Angle of Arrival (ML-AOA) estimation. The algorithm is initiated when

a MS is apprised of a CT transmission (1201). This may be accomplished by the MS itself detecting the CT transmission, or by the MS being notified of the CT transmission. In the latter case, it is preferable that the MS also be given an approximate TOA of the transmission and an information on the content of the transmission, to aid the MS in detecting the CT transmission.

The MS attempts to detect the CT transmission on some or all of the receive paths available to the MS associated with different antennas or antenna elements (1202). For each instance of the received transmission that the MS detects, the MS measures the SOA and/or POA (1203). For each pair of SOAs, the MS retrieves a likelihood function for AOA conditional on a function (such as ratio) of the observed SOAs. For each pair of POAs, the MS retrieves a likelihood function for AOA conditional on a function (such as ratio) of the observed POAs (1204).

The MS combines the likelihood functions for AOA by taking their product (1205). The ordinate of the maximum of the resulting likelihood function is taken as the AOA estimate (1206, 1208). Information from other sources (1207), such as AOA likelihood functions from other MSs, may be combined with the other likelihood functions.

Figure 13 illustrates an implementation of an algorithm for detecting CT transmissions. A correlation/combining function $z(\tau, F)$ is evaluated at trial values of τ and F. The ordinates (τ, F) of the maximum of $z(\tau, F)$ are taken as initial estimates of the TOA and Frequency of Arrival (FOA), respectively. A threshold for this maximum value may be used to determine whether or not a transmission has been detected.

Figure 14 illustrates a possible embodiment of a MS and Host. The antenna (1403) and RF Downconverter (1405) receive forward link transmissions (1401). The DSP Board (1407) converts the downconverted RF signal to digital signals and processes them to detect BS transmissions, measure their TOA, POA, SOA, and FOA, and decode messages transmitted by the BS.

The antenna (1404) and RF Downconverter (1406) receive reverse link transmissions (1402). The DSP Board (1408) converts the downconverted RF signal

to digital signals and processes them to detect CT transmissions, measure their TOA. POA, SOA, and FOA, and decode messages transmitted by the CT.

A Communication Controller (1409) interfaces between DSP Boards (1407, 1408) and some interface (1410) to the Host (1411). 1401 - 1409 comprise a MS.

The Host comprises one or more computers that receive information from MSs and estimate the location, speed, and DOT of a CT. Although not explicitly shown on Figure 14, the Host also sends information and orders to the MSs via the interface.

In a WLS, many factors affect the system performance, RF shadowing and flat fading, frequency offsets (including LOs drift and Doppler Shifts), clock errors, time delays, noise, multipath (selective fading), interference; geographical geometry of the MSs relative to the intended CT, and power control (of the CT's transmit power)

Each factor degrades the estimated location of the CT depending on the technology employed for extracting the independent equations required for location.

RF Transmission: More specifically, the Low Pass (LP) equivalent transmitted signal, $\tilde{s}(t)$, can be modeled as

$$\tilde{s}(t) = e^{-j2\pi(f_c + \Delta f_o)\tau_o} \, e^{j(2\pi\Delta f_o t + \zeta_o)} \, p(t - \tau_o) \tag{3}$$

and the RF transmitted signal, s(t), (see Figure 1) can be expressed as

$$s(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t} \, \tilde{s}(t) \right\} \tag{4}$$

where

- Re { . } denotes a real part operation;
- f_c is the nominal carrier frequency,
- Δf_0 is the frequency offset from f_c (usually unknown to the CT or BS since it is essentially an error in the frequency reference of the CT or BS),
- τ_0 is the time of transmission (also unknown to the MSs),
- ζ_0 is the phase offset of the transmitted carrier frequency $f_c + \Delta f_0$ (also unknown to the MSs),
- $j = \sqrt{-1}$ and
- p(t) is a band-limited baseband signal.

The signal s(t) may be transmitted by a BS or a CT, since both types of signals may contain information of interest in determining the location or velocity of a CT.

RF Reception: Then, the LP equivalent received signal, $\tilde{r}_{i,k}(t)$, through the k^{th} antenna at the i^{th} MS can be modeled as

$$\widetilde{r}_{i,k}(t) = G_{i,k}\, R_{i,k}^{-n}\, e^{j(\theta_{i,k}+\zeta_o)}\, e^{j2\pi(\Delta f_o+\delta f_{i,k})t}\, p(t - \tau_{i,k} - \Delta t_{i,k}) + w_{i,k}(t) + MP_{i,k}(t) + \widetilde{I}_{i,k}(t) \quad (5)$$

and the RF received signal, $r_{i,k}(t)$, (see Figure 2) can be expressed as

$$r_{i,k}(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t}\, \widetilde{r}_{i,k}(t) \right\} \quad (6)$$

where

- Re { . } denotes an operation which returns the real part of a complex number
- $G_{i,k}$ represents the gain (complex) due to the transmitting and receiving antennas from the CT to the k^{th} antenna of the i^{th} MS (a function of the two antenna patterns respectively),
- $R_{i,k}^{-n}$ represents the attenuation (real) due to the propagation channel, where
  - n is a real number (usually between 2 and 4) that depends on the channel and
  - $R_{i,k}$ is the range between the CT and the k^{th} antenna of the i^{th} MS,
- $\theta_{i,k} = \{ -2\pi(f_c + \Delta f_o + \delta f_{i,k}) (\tau_{i,k} + \Delta t_{i,k}) \} \bmod 2\pi \quad (7)$

  is the phase of the received RF signal at the k^{th} antenna of the i^{th} MS (more specifically at the connector of the k^{th} antenna of the i^{th} MS),

  where:
  - $\delta f_{i,k}$ is the frequency offset due to the Doppler shift over the propagation channel (a function of speed, v, and Direction Of Travel (DOT), φ).
  - $\tau_{i,k}$ is the **Time Of Arrival** (TOA) of the signal $r_{i,k}(t)$ at the k^{th} antenna of the i^{th} MS (a function of the range $R_{i,k}$).
  - $\Delta t_{i,k}$ is the overall group delay through the antenna of the CT to the k^{th} antenna of the i^{th} MS (usually a function of frequency),

- $w_{i,k}(t)$ represents the Additive White Gaussian Noise (AWGN, complex) due to thermal noise at the k^{th} antenna of the i^{th} MS (a function of temperature and bandwidth),
- $MP_{i,k}(t)$ represents all multipath components (complex) at the k^{th} antenna of the i^{th} MS (a function of the environment and of the elevation of the antennas), and
- $\tilde{I}_{i,k}(t)$ represents all low-pass equivalent interferences (both in-band and out-of-band) at the k^{th} antenna of the i^{th} MS.

Total RF Reception: In IS-95, a number of CTs transmit simultaneously over the same reverse link frequency band. In this model of a CDMA system, $\tilde{I}_i(t)$ represents all such CDMA signals excluding $\tilde{r}_i(t)$.

Baseband Reception: One or more IF stages down-convert the received RF signal, $r_{i,k}(t)$, to an analog baseband signal, $\hat{r}_{i,k}(t)$, which is equivalent to performing the following operation:

$$\begin{aligned}\hat{r}_{i,k}(t) &= e^{j2\pi f_c t}\ \tilde{r}_{i,k}(t)\ e^{-j2\pi(f_c+\Delta f_{i,k})t}\ e^{-j\zeta_{i,k}} \\ &= \tilde{r}_{i,k}(t)\ e^{-j2\pi\Delta f_{i,k}t}\ e^{-j\zeta_{i,k}}\end{aligned}$$

(8)

where

- $\Delta f_{i,k}$ is the frequency error between the Local Oscillators (LOs) in the k^{th} receiver at the i^{th} MS and the carrier frequency f_c; and
- $\zeta_{i,k}$ is the carrier phase of the LOs in the k^{th} receiver at the i^{th} MS.

From equations (5), (6) and (8), one can refer to:

- "$\psi_{i,k} = \theta_{i,k} - \zeta_{i,k} + \zeta_o$" as the **Phase Of Arrival** (POA) of the received signal, $\hat{r}_{i,k}(t)$; and

- "$f_{i,k} = \delta f_{i,k} - \Delta f_{i,k} + \Delta f_o$" as the **Frequency Of Arrival** (FOA) of the received signal, $\hat{r}_{i,k}(t)$.
- $SOA_{i,k} = G_{i,k} R_{i,k}^{-n}$ as the **Strength of Arrival** (SOA) of the received signal, $\hat{r}_{i,k}(t)$.
- $TOA_{i,k} = \tau_{i,k} + \Delta t_{i,k}$ as the **Time of Arrival** (TOA) of the received signal $\hat{r}_{i,k}(t)$.

Additionally, we define $w'(t) = \left[w_{i,k}(t) + MP_{i,k}(t) + \tilde{I}_{i,k}(t)\right] e^{-j2\pi f_c t}$ as the received and downconverted noise, interference, and multipath. In other words,

$$\hat{r}_{i,k}(t) = SOA_{i,k} \cdot \exp\left(j\psi_{i,k} + j2\pi f_{i,k} t\right) \cdot p\left(t - TOA_{i,k}\right) + w'(t) \tag{9}$$

There are various known means of extracting the complex baseband signal from a passband or IF signal, such as subsampling followed by digital quadrature demodulation.

Digital Reception: Finally, an Analog-to-Digital (A-to-D) Converter converts the baseband signal, $\hat{r}_{i,k}(t)$, to a digital signal, $\bar{r}_{i,k}(m)$, which is equivalent to performing the following operation:

$$\bar{r}_{i,k}(m) = \hat{r}_{i,k}(t)\Big|_{t=m T_s} + q_{i,k}(m)$$

where T_s is the sampling interval, m is the integer discrete-time index, and $q_{i,k}(m)$ is the quantization noise, which depends primarily on the number of bits and scaling of the A-to-D.

Five Steps for Positioning a CT using a network-based WLS:

1. Induce, Identify and categorize activity of a CT:

In some applications, activity of a CT will trigger the requirement for that CT to be located. For example, in the application of this invention to E911 services, the act of a CT originating a 911 call will trigger the need to locate that CT. Hence, the WLS System must monitor the activity of a CT for such a trigger.

In other applications, a powered-up CT has to be located passively, such as in the case for fleet management. This can happen based on the periodic registrations that the CT performs with a BS, or by active positioning. In the latter case, the Host can call the CT, receive its response through a number of MSs, then drop the call.

2. Detection:

There are generally two sources of information to be used to locate a CT using a network-based WLS: The Reverse Control/Access Channel and the Reverse Voice/Traffic Channel. When using the Reverse Control/Access Channel to locate a CT, the CT accesses the radio channel using a Random Access technique such as Aloha in AMPs and in IS-54, and slotted Aloha in CDMA, IS-136 and GSM.

The difficulty with locating over the Reverse Control/Access Channel is that a number of MSs must be able to detect the CT transmission even at low signal power. This problem is compounded when power control is activated at the CT, since in this case remote MSs receive the CT transmission well below the received signal at the serving BS. Several detection algorithms have been suggested in the literature such as Coherent combining, and Non-coherent combining.

Both techniques are sometimes unsuitable for WLS due to errors in the frequency estimation of the received signal. A novel detection is proposed in this patent that circumvents the errors in the estimated frequency: Group-coherent combining.

3. Measurement of Signal Parameters:

arious signal parameters exist in equation (9) that can lead to independent equations regarding the static location of the CT, i.e. regarding the coordinates, (x,y), of the CT location of the CT, such as

- the Strength of Arrival (SOA), $SOA_{i,k}$, of the carrier;
- the Phase of Arrival (POA), $\psi_{i,k}$, of the carrier;
- the baseband Waveform of Arrival (WOA), $p(t - TOA_{i,k})$; and
- the message content.

In addition, there is one source of information where one can extract an independent equation from equation (9) regarding the kinematic location of the CT, i.e. regarding the velocity, $\bar{\mathbf{v}}$, namely:

- the Frequency of Arrival (FOA), $f_{i,k}$, of the carrier.

4. Estimation of Location Parameter:

Based on the measured signal parameters of the CT, one can estimate the location parameters of the CT. For example:

- the SOA, $SOA_{i,k}$, can be used to estimate the range of the CT;
- the POA, $\psi_{i,k}$, can be used to estimate the AOA of the CT (**Solution I**);
- the WOA, $p(t - TOA_{i,k})$, can be used to estimate the TOA, $TOA_{i,k}$, of the CT (**Solution II, III & IV**);
- the FOA, $f_{i,k}$, can be used to estimate the velocity of the CT (**Solution V**);
- the combination of SOA, $SOA_{i,k}$, and POA, $\psi_{i,k}$, can be used to estimate the AOA of the CT (**Solution VI**).

5. Positioning of the CT:

Based on the estimated location parameters of the CT, one can estimate the location of the CT. Location examples include TOA/Range Positioning (Circular Multilateration); TDOA Positioning (Hyperbolic Multilateration); Hybrid TDOA Positioning (Circular Multilateration with TDOAs); AOA Positioning; AOA/TDOA Positioning; and Speed and Direction of Travel. Topics in Positioning of a CT

include: Effect of Geometry; Weighting of Observations; Blunder Detection; and Multiple Solutions. In the following sections, we expand further on the five steps for positioning a CT using a network-based WLS.

1. Induce, Identify and categorize activity of a CT:

1.1 Active CT:

In some applications, activity of a CT will trigger the requirement for that CT to be located. Hence, the WLS must monitor the activity of CT's for such a trigger. For example, in the application of this invention to E911 services, the act of a CT originating a 911 call will trigger the need to locate that CT. Another example is the case of a road accident where the airbag is inflated. In this case, the CT can be a simple transmitter that transmits a specific alert signal over the cellular bands.

MSs will monitor Access channel messages, identify Access channel origination messages, and extract the dialed number, the calling number, and possibly additional parameters. Selection criteria will be used to determine if the CT originating the call is to be located.

In order to identify activity of a CT, it is necessary to detect transmissions involving the CT. Both forward and reverse link transmissions may be of interest. Following detection of a transmission, its message content may be decoded and examined.

1.2 Passive CT

In some cases desirable to locate a CT that is not currently transmitting. There are two alternatives for locating such a CT: Passive Positioning; and Active Positioning. n **passive positioning**, the CT can be located as it performs regular tasks such as periodic registrations with a serving BS if the CT is stationary or registrations with new serving BSs as it enters new cells. In passive positioning, the timing of the last location fix is not crucial. It could be minutes or even hours in the past. Such a positioning is limited to some specific applications such as: RF Planning; Traffic Monitoring; and Fleet management.

In **active positioning**, the timing of the last fix is crucial. Such a positioning is important in applications such as: Recovery of stolen vehicles; Prevention of crimes; and Recovery of lost persons and pets.

In active positioning, the CT can be induced to produce transmissions that can be monitored by one or more MSs in order to determine the location of the CT. A CT can be induced to transmit on the Access channel by the Host initiating a call, through a telephone network connected to the cellular network, to the CT. This induces one or more BSs to transmit an Origination Message (see IS-95) addressed to the CT, on the Paging channel. If the CT is powered up and functional, it will respond by transmitting a response on the Access channel. In addition, a particular CT can be induced to transmit on the Access channel by transmitting a Paging message addressed to that particular CT with the VALID_ACK field of the Paging message set to 1, indicating to the CT that it must respond to the Paging message.

CTs can be configured, by an appropriate System Parameters Message from the cellular network, to transmit a Registration Message on the Access channel whenever some or all of the following events occur when the CT powers up, when the CT powers down, when the CT reaches a specified distance from the location of its last registration, and when a specified interval of time passes since the CT's last registration.

Some BSs could be configured to transmit a particular System Parameters Message content in order to induce CTs to transmit a Registration Message when in certain regions of the network. A CT can be induced to transmit on the Reverse Traffic channel by the Host initiating a call to the CT, and allowing the call to proceed to the point where the CT begins transmission on the Reverse Traffic channel. The Host may release the call after a specified interval of time, or after the CT's Reverse Traffic channel transmission have been detected by one or more MSs.

The Host may provide MSs with information to assist them with detecting MS transmissions. such as an approximate or estimated TOT, TOA, and/or FOA, or mobile ESN or message content of CT transmissions.

In both active and passive positioning, the CT could be a simple (miniaturized) transceiver, without the audio portion, which can emulate a cellular telephone in terms of transmitting over the reverse channel. In this case, the CT can be hidden in articles that would be normally carried by their corresponding transportation vehicle such as: Bracelets for persons; Collars for pets; and Black boxes under the hood/trunk of cars and trucks.

2. Detection and Acquisition

There are generally two sources of information to be used to locate a CT using a network-based WLS: The Reverse Control/Access Channel and the Reverse Voice/Traffic Channel. When using the Reverse Control/Access Channel to locate a CT, the CT accesses the radio channel using a Random Access protocol such as: Aloha in AMPs and in IS-54, and slotted Aloha in CDMA, IS-136 and GSM.

The difficulty with locating over the **Reverse Control/Access Channel** is that the same CT transmission must be detected and acquired by a minimum of three MSs in order to perform hyperbolic trilateration. This problem is compounded when power control is activated at the CT, since in this case remote MSs receive the CT transmission well below the received signal at the serving BS. This problem causes the probability of locating a CT to be less than 1.

On the other hand, when locating a CT using **the Reverse Voice/Traffic Channel** there are no detection problems to resolve. This is due to the fact that when the CT makes a call over a specific Reverse Control/Access Channel, such a request is monitored by a MS dedicated to monitor all activities over such a Reverse Control/Access Channel. The assignment of the Voice/Traffic Channel is performed by the serving BS over the Forward Control/Access Channel and is also monitored by the same MS. The MS transfers such information to the Host in order for the Host to decide whether to locate such a CT or not. In case the Host decides to locate such a CT, it notifies a minimum of three MSs to monitor the transmission of the CT over the Reverse Voice/Traffic Channel with enough side information regarding the CT

transmission. The side information allows the notified MSs to avoid (or at least to minimize) the need for detecting the CT transmission. In other words, the probability of locating a CT can be equal to 1.

In case the MSs must detect the CT transmission, several detection algorithms have been proposed.

2.1 Detection Model

The detection algorithm has at its disposal the received, down-converted, and sampled signal $\hat{r}_{i,k}(m)$, as defined in the following equation:

$$\hat{r}_{i,k}(m) = SOA_{i,k} \cdot \exp(j\psi_{i,k} + j2\pi f_{i,k} mT_s) \cdot p(mT_s - TOA_{i,k}) + w'(m) + q_{i,k}(m)$$

over the observation interval, $0 \le t \le T_{i,k}$ where, without loss of generality, p(t) is assumed to be an Access probe.

2.2 Detection Algorithm

The objective of the detection algorithm is to determine if the sought signal $p(t)$ is extant and resolvable in the received signal $\hat{r}_{i,k}(m)$, and if so, to provide coarse estimates of $TOA_{i,k}$, and $f_{i,k}$ denoted as $\hat{\tau}$ and $\hat{F}$ respectively. Figure 13 illustrates the detection algorithm at a high level. A correlation/combining function $z(\tau, F)$ is used as a measure of the correlation between the desired and received signals. $z(\tau, F)$ is evaluated over a set of ordinates called the trial values, (τ_i, F_j).

Specification of the algorithm requires defining the correlation/combining function and selecting trial values (τ_i, F_j).

2.3 Selection of Trial Values

Prior to detection, it is assumed that upper and lower bounds (denoted by subscripted "start" and "end") on $TOA_{i,k}$ and $F_{i,k}$ are known, hence it is only

necessary to use trial values for τ and F within the bounds of the following inequalities:

$$\tau_{start} \leq TOA_{i,k} \leq \tau_{end} \qquad F_{start} \leq F_{i,k} \leq F_{end}$$

It is only necessary to use trial values for τ and F within the bounds of the above inequalities. Next, there is the question of the number and distribution of trial values within the above bounds. As it is known that the CDMA baseband signal is bandlimited to approximately one half of the chip rate, a uniform spacing of one-half or one-quarter chip will be sufficient for trial values of τ. Hence, preferred values for spacing of τ_i are $\Delta\tau = 0.407\ \mu s$ or $0.203\ \mu s$ and the trial values of τ are

$$\tau_k = \tau_{start} + k\,\Delta\tau, \qquad k = 0, 1, 2, \ldots, N_\tau,$$

$$N_\tau = \left\lceil \frac{\tau_{end} - \tau_{start}}{\Delta\tau} \right\rceil$$

where $\lceil x \rceil$ denotes rounding to the nearest integer, and if equidistant between integers, rounding up.

To maintain a specified degradation due to frequency error, the spacing of trial values for F should be inversely proportional to the observation interval $T_{i,k}$. The preferred value for ΔF, the spacing of trial frequencies, is

$$\Delta F = \frac{0.1}{T_{i,k}}$$

The trial values of F are

$$F_k = F_{start} + k\,\Delta F, \qquad k = 0,1,2,\ldots, N_F,$$

$$N_F = \left\lceil \frac{F_{end} - F_{start}}{\Delta F} \right\rceil.$$

The trial values (τ_i, F_j) consist of all possible pairings of τ_i and F_j; there are $N_\tau \cdot N_F$ such pairs in total. Hence, $z(\tau_i, F_j)$ will be evaluated $N_\tau \cdot N_F$ times in order to search for a particular transmission.

2.4 Definition of Correlation/Combining Functions

Three candidates for the correlation/combining function are:

- $z_1(\tau, F)$, coherent correlation,
- $z_2(\tau)$, noncoherently combined correlation, and
- $z_3(\tau, F)$, the grouped coherent combined correlation.

The grouped coherent combined correlation is the preferred combining function for use in this invention.

2.4.1 Coherent Correlation

The coherent correlation is defined as

$$z_1(\tau, F) = \left| \sum_{m=0}^{T_{i,k}/T_s} \tilde{r}_{i,k}(m - \tau/T_s) p^*(mT_s) e^{-j2\pi F m T_s} \right|^2$$

The magnitude-square of the sum is taken in order to remove the effect of the unknown and arbitrary phase shift of the received signal and correlation result.

The performance of coherent correlation will equal or exceed the performance of the other two methods. The main drawback of coherent correlation is its computational complexity. As $T_{i,k}$ increases, ΔF must decrease linearly, which results in a corresponding increase in the number of trial values of F (see Equation $\Delta F = \frac{0.1}{T_{i,k}}$). At the same time, the complexity of computing each value of $z_1(\tau, F)$

also increases linearly. Hence, the overall complexity of the time-frequency search in the detection algorithm is a quadratic function of $T_{i,k}$.

2.4.2 Noncoherent combining

The complexity of computing $z_1(\tau, F)$ over multiple values of F can be avoided by correlating over subintervals of $T_{i,k}$, each of duration T_{group}, and combining these subinterval correlations noncoherently to yield $z_2(\tau)$:

$$z_2(\tau) = \sum_{n=0}^{\lfloor T_{i,k}/T_{group} \rfloor} |c(n,\tau)|^2$$

The correlations over the subintervals, $c(n,\tau)$, are referred to as subcorrelations:

$$c(n,\tau) = \sum_{m=\lfloor nT_{group}/T_s \rfloor}^{\lfloor (n+1)T_{group}/T_s \rfloor - 1} \tilde{r}_{i,k}(m - \tau/T_s) p^*(mT_s)$$

An optional step which reduces the effect of noise is to filter the sequence of subcorrelation results prior to noncoherent combining to remove signal components outside of the range of expected frequency offsets, $F_{start} \le F \le F_{end}$. The preferred embodiment is a transversal filter with taps $h(n)$, $-N_h/2 \le n \le N_h/2$, having a passband between the frequencies $2\pi F_{start} T_{group}$ and $2\pi F_{end} T_{group}$ (in radians per sample).

Evaluating the incoherent combining function over the trial values of τ will yield a TOA estimate, $\hat{\tau}$. In order to obtain the FOA estimate $\hat{F}$, the coherent combining function $z_1(\tau, F)$ is then evaluated at $\hat{\tau}$ and over the trial values F_k. The trial value F_k which maximizes $z_1(\hat{\tau}, F_k)$ is taken as the FOA estimate $\hat{F}$.

2.4.3 Grouped Coherent Combining

This third approach is capable of achieving detection performance close to that of coherent integration, with significantly reduced complexity. Subcorrelations $c(k,\tau)$ are computed as described for incoherent combining, and are then coherently combined at the trial values of F.

$$z_3(\tau,F)=\left|\sum_{n=0}^{T_{i,k}/T_{group}} c(n,\tau)\cdot e^{-j2\pi F n T_{group}}\right|^2$$

In some circumstances, it may be computationally efficient to compute $z_3(\tau,F)$ by taking the Fast Fourier Transform (FFT) of $c(n,\tau)$ over n. In this case, the frequency spacing of the FFT samples is $\Delta F_{FFT}=1/T_{i,k}$. This spacing can be reduced to meet the criteria of Equation $\Delta F=\frac{0.1}{T_{i,k}}$ by zero-padding $c(n,\tau)$ before computing the FFT.

3. Measurement of Signal Parameters

3.1 Measurement of TOA and FOA

In this section, the coarse estimates of TOA and FOA, $\hat{\tau}$ and $\hat{F}$, will be referred to as $\hat{\tau}_{coarse}$ and $\hat{F}_{coarse}$. These estimates are refined by recomputing the subcorrelations with a frequency offset of $\hat{F}_{coarse}$,

$$c(n,\tau)=\sum_{m=\lfloor nT_{group}/T_s\rfloor}^{\lfloor (n+1)T_{group}/T_s\rfloor-1} \hat{r}_{i,k}(m-\tau/T_s)p^*(mT_s)e^{-j2\pi\hat{F}_{coarse}mT_s},$$

and repeating the detection algorithm with a finer spacing of trial values localized around the coarse estimates $\hat{\tau}_{coarse}$ and $\hat{F}_{coarse}$. The preferred fine trial values are:

$$\Delta\tau_{fine} = 0.102\ \mu s, \qquad \Delta F_{fine} = \frac{0.25}{T_{i,k}}$$

$$\tau_k = \hat{\tau}_{coarse} + k(0.102\ \mu s), \qquad k = -16, -15, \ldots, 16$$

$$F_k = \hat{F}_{coarse} + k\frac{0.025}{T_{i,k}}, \qquad k = -8, -7, \ldots, 8$$

Evaluation of $z_3(\tau, F)$ takes into account that the subcorrelations are offset by $\hat{F}_{coarse}$.

$$z_{3,fine}(\tau, F) = \left| \sum_{n=0}^{T_{i,k}/T_{group}} c(n,\tau) \cdot e^{-j2\pi(\hat{F} - F_{coarse})nT_{group}} \right|^2$$

This refined TOA estimate, like the coarse TOA estimate, is a measurement of the peak of the received signal. It is desirable to measure the leading edge or first arrival for the purpose of position estimation. This can be done by applying rising-edge detection or Super-Resolution to the refined correlation results. If desired, the FOA estimate can also be improved by Super-Resolution.

3.2 Measurement of POA

An appropriate correlation/combining function is applied to the received signal, without the final step of magnitude-squaring as is used in detection, and the phase of the result is taken as the POA of the desired signal.

3.3 Measurement of SOA

The magnitude of the correlation/combining function evaluated at the best available estimates of TOA and FOA may be used as an estimate of the SOA. The uncorrupted SOA is $SOA_{i,k} = G_{i,k} R_{i,k}^{-n}$. We may estimate the SOA as

$$\hat{SOA}_{i,k} = z(\hat{\tau}, \hat{F}) \quad \text{measured at antenna k of } i^{th} \text{ BS.}$$

This estimate of SOA will be corrupted by noise, interference, and errors in other estimated parameters such as POA, FOA, and TOA.

3.4 Message Decoding

Message identification and fields are defined by applicable standards (IS-95, J-STD-008). The received signal can be decoded according to these published standards. Certain messages contain information which can be used to estimate the mobile location.

3.4.1 Pilot Strength Measurement Message

The Pilot Strength Measurement message is transmitted by the CT over the reverse traffic channel, and for one or more pilots, contains the following information

PILOT_PN_PHASE	This identifies the TOA of the pilot signal measured at the mobile to a resolution of one chip. The pilot PN phase offset (in units of 64 chips) can be determined from this number, in order to identify the BS transmitting this pilot signal.
PILOT_STRENGTH	This is the CT's estimate of the SOA of the pilot signal at the CT. As the forward and reverse link path losses will generally be close in value, this SOA estimate can be used in the same manner as reverse link SOA estimates to aid in estimating the CT location.

Multiple PILOT_PN_PHASE measurements can be processed as TOA signals to obtain a TDOA position estimate for the CT.

3.4.2 Access Channel Messages

The IS-95B standard allows for a CT to include PILOT_PN_PHASE and PILOT_PN_STRENGTH information for one or more pilots in Access channel messages. These messages can be decoded by a MS and used in the same manner as described above for the Pilot Strength Measurement Message.

4. Estimation of Location Paramters:

4.1 SOA:

4.1.1 $SOA_{i,k} = G_{i,k}R_{i,k}^{-n}$ to estimate Range, $R_{i,k}$:

In the static case, the first source, $SOA_{i,k} = G_{i,k}R_{i,k}^{-n}$, can be used to estimate the range $R_{i,k}$. However, the estimation of $R_{i,k}$ from $G_{i,k}R_{i,k}^{-n}$ is unreliable, even if $G_{i,k}$ is known, due to the nature of the radio channel where RF shadowing and flat fading can deviate the value of "n" in "$R_{i,k}^{-n}$" from 2 (for Line Of Sight (LOS)) to 4 (for an urban environment, as shown in Hata, M., "Empirical Formula for Radio Propagation Loss in Land Mobile Radio Services," *IEEE Transactions on Vehicular Technology*, Vol. VT-29, No. 3, August 1980), or even 6 in heavy urban environments. Hence, unless LOS is guaranteed between the CT and the k^{th} antenna at the ith MS, $R_{i,k}^{-n}$ can only offer an accuracy of a few kilometers for $R_{i,k}$. In the case when LOS is guaranteed (e.g. in a flat environment such as in the sea or over a lake) and $G_{i,k}$ is known to the i^{th} MS, then "n" can be chosen to be 2.

4.1.2 SDOA (Strength Difference of Arrival):

As the absolute transmit power level of the CT will in general be unknown to the MS, multiple measurements of $R_{i,k}^{-n}$ from different MSs may be compared to estimate the relative distance of the CT from each MS. In other words, assuming that "n" is constant for some MSs, one can use SOA combined with the knowledge of the antenna gain patterns (i.e. the variation of $G_{i,k}$ with the AOA γ_i) to estimate the AOA of the signal transmitted from the CT to the MS. The current patent application introduces a novel method of measuring the relative gain patterns between antennas, and estimating AOA. The assumption for "n" being constant for some MSs is valid when the antennas at the MSs are closely spaced and elevated relative to the antenna of the CT.

Due to the nature of IS-95 and J-STD-008 forward link power control, a MS can estimate the forward link path loss from the power level of the forward traffic channel. This may be used independently of observations from other MSs to estimate $R_{i,k}$. However, this estimation is subject to the same unreliability as the reverse link path loss range estimation.

4.2 POA:

4.2.1 $\psi_{i,k}$ to estimate AOA:

The second source, the POA

$$\psi_{i,k} = \{ -2\pi(f_c + \Delta f_o + \delta f_{i,k})(\tau_{i,k} + \Delta t_{i,k}) + \Delta\zeta_{i,k} \} \bmod 2\pi \qquad (10)$$

can be used to estimate the AOA, $\gamma_{i,k}$, where $\Delta\zeta_{i,k}$ is defined as $\zeta_o - \zeta_{i,k}$. The relationship between the POA, $\psi_{i,k}$, and the AOA, $\gamma_{i,k}$, is explained as follows.

For simplicity of notation we first assume that:

- the k^{th} antenna at the i^{th} MS is **antenna$_1$**, while
- the m^{th} antenna also at the i^{th} MS is **antenna$_2$**.

We further assume that the CT is far from the i^{th} MS with respect to the baseline, $d_{i,1,2}$, between **antenna$_1$** and **antenna$_2$**. Such an assumption implies that the received wavefront is planar, i.e. $\gamma_{i,1} \cong \gamma_{i,2} \cong \gamma_i$, where:

- $\gamma_{i,1}$ is the Angle Of Arrival (**AOA**) of $r_{i,1}(t)$ at **antenna$_1$**,
- $\gamma_{i,2}$ is the AOA of $r_{i,2}(t)$ at **antenna$_2$**, and
- γ_i is defined as the angle formed between:
- the line joining the CT (301) and the i^{th} MS and,
- the line joining the two antennas at the i^{th} MS;

in a clockwise manner from the line formed by the CT and the i^{th} MS to the line formed by the two antennas.

This in turn implies that the Phase Difference of Arrival (PDOA), $(\psi_{i,1} - \psi_{i,2})$, is related to the angle γ_i through the following relation:

$$\frac{2\pi d_{i,1,2}}{\lambda}\cos(\gamma_i) = (\psi_{i,1} - \psi_{i,2}) \bmod 2\pi \qquad (11)$$

where:

- $\psi_{i,1}$ is the Phase Of Arrival (**POA**) of $r_{i,1}(t)$ at **antenna$_1$**; and
- $\psi_{i,2}$ is the POA of $r_{i,2}(t)$ at **antenna$_2$**.

The solution for γ_i in (11) is

$$\gamma_i = \pm\cos^{-1}\left\{\frac{\lambda}{2\pi\, d_{i,1,2}}((\psi_{i,1} - \psi_{i,2}) \bmod 2\pi + 2\pi k)\right\}$$

(12)

where k in (12) is an integer that has to satisfy the following condition:

$$-1 \le \frac{\lambda}{d_{i,1,2}} \left\{ \frac{(\psi_{i,1} - \psi_{i,2}) \bmod 2\pi}{2\pi} + k \right\} \le 1 \qquad (13)$$

For example, when $d_{i,1,2} = \lambda$, we have the following possible solutions for k:

$$\text{when } \frac{(\psi_{i,1} - \psi_{i,2}) \bmod 2\pi}{2\pi} = -1, \quad \text{we have } k = 0, 1 \text{ or } 2;$$
$$\text{when } \frac{(\psi_{i,1} - \psi_{i,2}) \bmod 2\pi}{2\pi} = +1, \quad \text{we have } k = 0, -1 \text{ or } -2;$$
$$\text{when } \frac{(\psi_{i,1} - \psi_{i,2}) \bmod 2\pi}{2\pi} = -1/2, \quad \text{we have } k = 0 \text{ or } 1;$$
$$\text{when } \frac{(\psi_{i,1} - \psi_{i,2}) \bmod 2\pi}{2\pi} = +1/2, \quad \text{we have } k = 0 \text{ or } -1;$$
$$\text{when } \frac{(\psi_{i,1} - \psi_{i,2}) \bmod 2\pi}{2\pi} = 0, \quad \text{we have } k = 0, 1 \text{ or } -1;$$

(14)

Some of the solutions in (14) are trivial. As $d_{i,1,2}$ becomes larger than λ, we have more nontrivial solutions. Even though having more than one solution implies ambiguity, it is possible to resolve the ambiguity using redundant observations based on Least-Squares Techniques as explained later.

4.2.2 $\psi_{i,k}$ to estimate TOA:

It is also possible to use the POA, $\psi_{i,k}$, in equation (10) to estimate $\tau_{i,k}$. A drawback in using $\psi_{i,k}$ to estimate $\tau_{i,k}$ is the "mod 2π" operation in (10) which implies that there can be a large integer ambiguity in such an estimation. For example, in TDOA positioning, a pair of TOAs, $\tau_{i,k}+\Delta t_{i,k}$ and $\tau_{j,m}+\Delta t_{j,m}$, is needed per independent equation. In this case, the amount of ambiguity is a function of the baseline between the two receiving antennas, i.e. between

- the k^{th} antenna in the i^{th} MS and

- the m^{th} antenna in the j^{th} MS

with respect to the wavelength corresponding to the frequency: $f_c + \Delta f_o + \delta f_{i,k}$ in (10). This is shown in equation (15):

$$\tau_{i,k} - \tau_{j,m} = -\{(\psi_{i,k} - \psi_{j,m}) - (\Delta\zeta_{i,k} - \Delta\zeta_{j,m}) + 2\pi n\}/2\pi f_c - (\Delta t_{i,k} - \Delta t_{j,m}) + \text{extra term} \quad (15)$$

where

- $\tau_{i,k}$ corresponds to the TOA at the k^{th} antenna of the i^{th} MS;
- $\tau_{j,m}$ corresponds to the TOA at the m^{th} antenna of the j^{th} MS;
- n is the integer ambiguity; and
- the extra term in (15) is due to the existence of
  - Δf_o in (10) which depends on the error in the CT LOs relative to f_c; and to
  - $\delta f_{i,k}$ in (10) which depends on the velocity $\bar{\mathbf{v}}$ of the CT and the wavelength λ corresponding to f_c.

In the IS-95 and J-STD-008 standards, the CT frequency, $f_c + \Delta f_o$, can deviate by up to 0.05 parts per million (i.e. by up to 95Hz for a 1900MHz carrier frequency). Furthermore, in cellular telephony in North America, the carrier frequency, f_c, can take values around 800MHz (with a wavelength λ of around 37.5cm) or values around 1.9GHz (with a wavelength λ of around 15.8cm). This implies that for a velocity of 100km/hr δf_i corresponds to:

$-40\text{Hz} > \delta f_i > 40\text{Hz}$ for f_c = 800MHz, or to

$-95\text{Hz} > \delta f_i > 95\text{Hz}$ for f_c = 1.9GHz.

In conclusion:

1. $f_c >> \delta f_{i,k}$ and $f_c >> \Delta f_0$, i.e. the extra term in (15) is negligible; and

2. the amount of ambiguity in (15) can be potentially large unless the baseline between the two receiving antennas is small with respect to the wavelength, λ, corresponding to the frequency: f_c. We refer to such a solution as **Solution I.**

__Solution II:__ When the baseline between the k^{th} antenna at the i^{th} MS and the m^{th} antenna at the j^{th} MS is small relative to the wavelength, λ, we assume without loss of generality that the two antennas belong to the same MS. When the MS is collocated with a BS, the two antennas can be:

- cellular diversity antennas;
- cellular sector antennas; or
- any other types of antennas, deployed solely for location. Such types include:
  - indoor antennas located inside the BS housing;
  - outdoor antennas located on the roof of the BS housing; and
  - outdoor antennas located on the cellular tower.

In this case, it is possible to generate a solution using either TDOA or PDOA. The TDOA solution between the two antennas is a hyperbola while the PDOA solution between the two antennas is a line. Both solutions approximate the exact solution and coincide asymptotically, i.e. the PDOA line and the TDOA hyperbola coincide at infinity.

In processing $\psi_{i,k}$ to estimate either $\tau_{i,k}$ or γ_i, we have the following sources of errors:

- **__The effect of noise, $w_{i,k}(t)$, on γ_i:__**

  When using a linear array of antennas to estimate the AOA of an RF signal approximated as a planar wavefront (i.e. assuming a distant RF source), the Cramer-Rao Lower Bound on the variance, $\mathrm{var}(\hat{\gamma}_i)$, of the estimated AOA, $\hat{\gamma}_i$, is equal to

$$\operatorname{var}(\hat{\gamma}_i)\big|_{Tone} \geq \frac{12c^2}{SNR_{i,k}\big|_{Tone} \times 4\pi^2 \times M \times (M^2-1) \times d^2 \times \sin^2\gamma_i \times f_m^2}$$

(16)

where

- $\operatorname{var}(\hat{\gamma}_i)\big|_{Tone}$ is the variance of the estimate $\hat{\gamma}_i$ of the bearing γ_i
- $SNR_{i,k}\big|_{Tone} = A_{i,k}^2/(2\sigma_n^2)$,
- $A_{i,k}$ is the amplitude of the tone
- σ_n^2 is the noise variance,
- M is the number of elements in the antenna array,
- d is the distance between antenna elements,
- f_m is the frequency of the tone, and
- c is the speed of light.

- **<u>The effect of noise, $w_{i,k}(t)$ on $\psi_{i,k}$:</u>**

The Cramer-Rao Lower Bound provides a lower bound on the effect of AWGN on the variance, $\operatorname{var}(\hat{\psi}_{i,k})\big|_{Tone}$, of the estimate, $\hat{\psi}_{i,k}$, of the phase $\psi_{i,k}$ for a tone of frequency f_m:

$$\operatorname{var}(\hat{R}_{i,k})\big|_{Tone} = \left(\frac{\lambda}{2\pi}\right)^2 \operatorname{var}(\hat{\psi}_{i,k})\Big|_{Tone} \geq \frac{c^2}{SNR_{i,k}\big|_{Tone} \times N_{i,k} \times 4\pi^2 f_m^{\,2}}$$

(17)

where

- $\operatorname{var}(\hat{R}_{i,k})\big|_{Tone}$ is the variance of the estimate, $\hat{R}_{i,k}$, of the range $R_{i,k}$,
- λ is the wavelength of the tone,
- f_m is the frequency of the tone corresponding to λ (i.e. $f_m=c/\lambda$).

- $SNR_{i,k}\big|_{Tone} = A_{i,k}^2/(2\sigma_n^2)$ where $SNR_{i,k}$ is the Signal-to-Noise Ratio at the k^{th} antenna of the i^{th} MS,
- $A_{i,k}$ is the amplitude of the tone at the k^{th} antenna of the i^{th} MS,
- σ^2_n is the noise variance,
- $N_{i,k}$ is the number of samples (which is directly related to the observation interval $T_{i,k}$ through $T_{i,k}=N_{i,k}/f_s$ where f_s is the sampling frequency),
- c is the speed of propagation.

- **<u>Phase offsets:</u>**

  The phase of the tone f_m is shifted by $\Delta\zeta_{i,k}$. In other words, $\Delta\zeta_{i,k}$ has to be estimated otherwise the phase $\psi_{i,k}$ is distorted.

- **<u>time delays, $\Delta t_{i,k}$:</u>**

  The propagation delay $\tau_{i,k}$ is affected by $\Delta t_{i,k}$ which represents the system delay through the antenna, cables, filters, amplifiers, etc. $\Delta t_{i,k}$ has to be estimated otherwise the propagation delay can be prolonged significantly.

- **<u>multipath, $MP_{i,k}(t)$:</u>**

  In TDOA, the multipath $MP_{i,k}(t)$ is equivalent to extra delay over the propagation channel and has to be either estimated and removed, or mitigated. In the case where the phase estimate is used to solve for the AOA of the received signal $r_{i,k}(t)$, the effect of multipath is to shift the AOA of $r_{i,k}(t)$ by some amount depending on the AOA of $MP_{i,k}(t)$ and its magnitude.

- **<u>interference, $\tilde{I}_{i,k}(t)$:</u>**

Depending on the level of interference, $\tilde{I}_{i,k}(t)$ can have a drastic effect on the accuracy of the estimated phase and may saturate the RF front end of the receiver. Its effects can be mitigated with both analog and digital hardware, as well as adequate software, whether it is in-band or out-of-band.

4.3. WOA

4.3.1 $p(t - TOA_{i,k})$ to estimate TOA:

The last (and most common) source of information one can use to extract an independent equation for the static location of the CT is

$$p(t - TOA_{i,k}) \tag{18}$$

which can be used to estimate the TOA, $TOA_{i,k}$.

Solution II: The most common method for estimating the TOA from $p(t - TOA_{i,k})$ is to cross-correlate $p(t - TOA_{i,k})$ with $p(t)$ (i.e. to cross-correlate $r_{i,k}(t)$ with $p(t)$). Equivalently, one can estimate the TDOA, $TOA_{i,k} - TOA_{j,m}$, between $TOA_{i,k}$ at the k^{th} antenna of the i^{th} MS and $TOA_{j,m}$ at the m^{th} antenna of the j^{th} MS by cross-correlating: $p(t - TOA_{i,k})$ with $p(t - TOA_{j,m})$, i.e. to cross-correlate $r_{i,k}(t)$ with $r_{j,m}(t)$. When the i^{th} MS and the j^{th} MS do not exist in the same location, one has to transfer both $r_{i,k}(t)$ and $r_{j,m}(t)$ to the same location. This can be costly and time consuming depending on the size and bit resolution of $r_{i,k}(t)$ and $r_{j,m}(t)$. Moreover, both $p(t - TOA_{i,k})$ and $p(t - TOA_{j,m})$ are obtained from $r_{i,k}(t)$ and $r_{j,m}(t)$ respectively, i.e. they are both noisy. A more efficient and less noisy method is to cross-correlate $p(t - TOA_{i,k})$ with $p(t)$ at the i^{th} MS, as mentioned above, then transfer the estimated value of $\tau_{i,k}$ to the host. In this case, $p(t)$ has to be known at the i^{th} and j^{th} MSs which places a constraint on $p(t)$.

Once the TOA, $TOA_{i,k}$, is estimated using **Solution II** above, the range, $R_{i,k}$, between the k^{th} antenna at the i^{th} BS, and the CT can also be estimated through equation (19):

$$R_{i,k} = (\tau_{i,k} - \tau_o)\, c \tag{19}$$

where c is the speed of propagation. The time of transmission, τ_o, in (11) is usually unknown to the MSs. One may either:

1. estimate it, then use the estimated value in TOA positioning, or
2. remove it using TDOA positioning.

Both TOA and TDOA positioning are explained later in the patent.

In TOA positioning, a possible method to estimate τ_o is to estimate the Round Trip Delay (RTD) between: the transmission from an active BS to a CT and the response of the CT to the transmission of the active BS.

In this case,

$$2R_{i,k} = (2\tau_{i,k} - \tau_{BS})\, c \tag{20}$$

where τ_{BS} is the time of transmission from the BS to the CT and $2\tau_{i,k}$ is the TOA of the response of the CT to the BS.

In TDOA positioning, the time of transmission, τ_o, is removed using an extra independent equation.

It is also possible to estimate the TOA, $\tau_{i,k}$, from phases of tones generated from $p(t - \tau_{i,k} - \tau_o - \Delta t_{i,k})$. We refer to such a solution as **Solution III** which is particularly useful when $p(t - \tau_{i,k} - \tau_o - \Delta t_{i,k})$ is either periodic or cyclo-stationary. When $p(t - \tau_{i,k} - \tau_o - \Delta t_{i,k})$ is periodic, its Fourier series representation would reveal such tones. When $p(t - \tau_{i,k} - \tau_o - \Delta t_{i,k})$ is cyclo-stationary, performing a nonlinear operation on it would reveal such tones. In IS-95B, $p(t - \tau_{i,k} - \tau_o - \Delta t_{i,k})$ is neither periodic nor cyclo-stationary (except between chips). On the other hand, $p(t - \tau_{i,k} - \tau_o - \Delta t_{i,k})$ is cyclo-stationary: in GPS, in both TDMA standards: IS-136 and GSM, and in wideband CDMA (3G CDMA).

Solution III: When $\tau_{i,k}$ is estimated indirectly based on the phases of tones generated from $p(t - \tau_{i,k} - \tau_o - \Delta t_{i,k})$, an integer ambiguity can still exist in the solution unless the wavelength of the selected tones is large with respect to the range between the CT and the k^{th} antenna at the i^{th} MS. The selected tones are discussed below where a solution for the integer ambiguity is presented.

It is also possible to use the estimated TDOA solution, $\tau_{i,k} - \tau_{j,m}$, to estimate the AOA, $\gamma_{i,j}$. We refer to such a solution as **Solution IV**.

Solution IV: In order to estimate $\gamma_{i,j}$ from the TDOA solution, $\tau_{i,k} - \tau_{j,m}$, it is assumed that the CT is far from both the k^{th} antenna at the i^{th} MS and the m^{th} antenna at the j^{th} MS with respect to their baseline, $d_{i,j,k,m}$. As mentioned previously, such an assumption practically implies that:

1. Both antennas exist at the same MS.
2. The received wavefront is planar, i.e. $\gamma_{i,1} \cong \gamma_{i,2} \cong \gamma_i$, where
   - $\gamma_{i,1}$ is the Angle Of Arrival (**AOA**), at antenna$_1$ of the ith MS,
   - $\gamma_{i,2}$ is the AOA at antenna$_2$ of the ith MS, and
   - γ_i is defined as the angle formed between:
   - the line joining the CT (301) and the ith MS and,
   - the line joining the two antennas at the ith MS

   in a clockwise manner from the line formed by the CT and the ith MS to the line between the two antennas.
3. Equation (21) relates the angle γ_i to the Time Difference of Arrival (TDOA), $\tau_{i,1} - \tau_{i,2}$, as follows

$$\frac{d_{i,1,2}}{c}\cos(\gamma_i) = \tau_{i,1} - \tau_{i,2} \qquad (21)$$

where

- $d_{i,1,2}$ is the distance between the first antenna at the ith MS and the second antenna at the ith MS; and
- c is the speed of propagation.

The advantage in estimating the AOA, γ_i, using $p(t - \tau_{i,k} - \tau_o - \Delta t_{i,k})$ in equation (18) from equation (22):

$$\gamma_i = \pm\cos^{-1}\left\{\frac{c}{d_{i,1,2}}(\tau_{i,1} - \tau_{i,2})\right\} \qquad (22)$$

instead of using $\psi_{i,k}$ in (10) from equation (23):

$$\gamma_i = \pm\cos^{-1}\left\{\frac{\lambda}{2\pi\, d_{i,1,2}}(\psi_{i,1} - \psi_{i,2} + 2\pi\, k)\right\} \qquad (23)$$

is the fact that there are no ambiguities in equation (22) except for the $\pm$ in the solution of γ_i, while equation (23) can have a number of ambiguities depending on the value of the integer k.

The disadvantages in estimating the AOA γ_i using $p(t - \tau_{i,k} - \tau_o - \Delta t_{i,k})$ in equation (18) instead of using $\psi_{i,k}$ in (10) are:

1. a small baseline is required between the two antennas; and
2. the noise affects the variance, $\mathrm{var}(\hat{\tau}_{i,k})\big|_{p(t)}$, of $\hat{\tau}_{i,k}$ more substantially than it affects the variance, $\mathrm{var}(\hat{\psi}_{i,k})$, of $\hat{\psi}_{i,k}$.

The second disadvantage can be explained by comparing the Cramer-Rao Lower Bound for $\hat{\psi}_{i,k}$:

$$\left(\frac{\lambda}{2\pi}\right)^2 \mathrm{var}(\hat{\psi}_{i,k})\Big|_{Tone} \geq \frac{c^2}{SNR_{i,k}\big|_{Tone} \times N_{i,k} \times 4\pi^2 f_m^{\ 2}} \tag{24}$$

with the CRLB for $\hat{\tau}_{i,k}$:

$$c^2\,\mathrm{var}(\hat{\tau}_{i,k})\Big|_{p(t)} \geq \frac{c^2}{SNR_{i,k}\big|_{p(t)} \times 4\pi^2 BW^2} \tag{25}$$

Assuming that $SNR_{i,k}\big|_{Tone} \times N_{i,k}$ in (24) is equal to $SNR_{i,k}\big|_{p(t)}$ in (25), then the difference between (24) and (25) is $f_m^{\ 2}$ in (24) compared to BW^2 in (25). In IS-95 and J-STD-008 the BW is approximately equal to 1.23MHz while f_m can be equal to the carrier frequency f_c, i.e. either 800MHz or 1.9GHz. The ratio between the two values in dB is 56.26dB for f_c=800MHz and 63.77dB for f_c=1.9GHz. In both cases, the difference is large. Nonetheless, $p(t - \tau_{i,k} - \Delta t_{i,k})$ in (18) is suitable for TDOA positioning while $\psi_{i,k}$ in (10) is suitable for AOA positioning as explained here:

- Using $\psi_{i,k}$ in (10) to estimate the AOA, γ_i, we have a lower-bound of 5×10^{-5} radians^2 for a SNR, $SNR_{i,k}\big|_{Tone} \times N_{i,k}$, of 30dB and for a distance, $d_{i,1,2}$, of one wavelength, i.e. 0.375m. This is equivalent to having a standard

deviation for $\hat{\gamma}_{i,}$ of 7.07×10^{-3} radians, which corresponds to a range error of 7.11 meters for every kilometer range between the MR and the antennas.

- On the other hand, $p(t - \tau_{i,k} - \tau_o - \Delta t_{i,k})$ in (18) is suitable for TDOA positioning since in this case the baseline between antennas does not have to be small. For example, assuming the SNR, $SNR_{i,k}\big|_{p(t)}$, in equation (25) to be 10dB for IS-95, the range $R_{i,k}$ has a variance of 150.69meters^2 or equivalently $\hat{R}_{i,k}$ has a standard deviation of 12.28meters.

In processing $p(t - \tau_{i,k} - \tau_o - \Delta t_{i,k})$ to estimate $\tau_{i,k}$, we have the following sources of errors:

- **<u>noise, $w_{i,k}(t)$:</u>**

  The Cramer-Rao Lower Bound provides a lower bound on the effect of AWGN on the variance, $\mathrm{var}(\hat{\tau}_{i,k})\big|_{p(t)}$, of the estimate of the delay $\tau_{i,k}$:

$$\mathrm{var}(\hat{R}_{i,k})\Big|_{p(t)} = c^2\,\mathrm{var}(\hat{\tau}_{i,k})\Big|_{p(t)} \geq \frac{c^2}{SNR_{i,k}\big|_{p(t)} \times 4\pi^2 BW^2}$$

(26)

where

- $\mathrm{var}(\hat{R}_{i,k})\big|_{p(t)}$ is the variance of the estimate, $\hat{R}_{i,k}$, of the range $R_{i,k}$
- BW is the RMS bandwidth of p(t),
- $SNR_{i,k}\big|_{p(t)} = 2E_{i,k} / N_o$,
- $E_{i,k}$ is the energy of $r_{i,k}(t)$,
- N_o is the noise Power Spectral Density, and
- c is the speed of light.

- **The effect of Bandwidth, BW:**

Equation (26) demonstrates that the bandwidth of the signal plays an important role in the accuracy of the wireless location system. In IS-95, the radio frequency (RF) channels are spaced by 1.23 MHz which is a comparable BW relative to systems designed primarily for location such as Global Positioning Systems (GPS) with a BW of 1MHz over Standard Positioning Services (SPS) channels. The preferred embodiment of location system, including host, according to the current patent application is network-based while GPS is handset-based. In GPS, the location system initially uses a conventional sliding correlator (similar to **Solution II**) in the handset to obtain a set of pseudo-ranges (one pseudo-range per satellite) (see e.g. Spilker, J.J., "GPS Signal Structure and Performance Characteristics," *Global Positioning System, Volume I,* The Institute of Navigation, Washington D.C., 1980). The pseudo-ranges are then used in multi-lateration to obtain a position fix of the GPS receiver. A typical accuracy for a commercial one point (i.e. no differential reception) GPS receiver with SPS is around 30m RMS without Selective Availability (SA).

In order to achieve a comparable accuracy using IS-95 (assuming no multipath), **Solution II** suggests that a conventional sliding correlator is required at each MS with 8 samples per chip. The sliding correlator provides a TOA estimate of the transmitted radio signals which is followed by a hyperbolic (differential) multi-lateration of all the TOA estimates at some central site. The reason for requiring 8 samples per chip is that the correlation function from which a TOA may be estimated has a resolution which is limited to that of the Fourier transform. The traditional resolution bound on Fourier-based methods is the Rayleigh resolution criterion as shown in Haykin, S., "*Adaptive Filter Theory,*" 2nd Edition, Prentice Hall, Englewood Cliffs, NJ, 1991.

In order to reduce the required number of samples per chip, while maintaining good accuracy (even with multipath), further processing using SR algorithms often yields a result with higher resolution. This was shown by Dumont, L.R., et al., "Super-resolution of Multipath Channels in a Spread Spectrum Location System," *IEE Electronic Letters,* Vol. 30, No. 19, pp. 1583-1584, September 15, 1994 and as

shown by Fattouche et al., U.S. Patent No. 5,570,305 issued Oct., 1996, and as shown by Ziskind, I. et al., "Maximum Likelihood Localization of Multiple Sources by Alternating Projection," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. ASSP-36, No. 10, October, 1988.

- **<u>The Effect of the Observation Interval, $T_{i,k}$:</u>**

The Observation interval, $T_{i,k}$, is directly related to the energy $E_{i,k}$ in the received signal $r_{i,k}(t)$ at the k^{th} antenna of the i^{th} MS since

$$E_{i,k} = \int_{0}^{T_{i,k}} \left| r_{i,k}(t) \right|^2 dt \tag{27}$$

It is also related to the steady state response of a filter in such a way that the response of the filter reaches its steady state as long as

$$T_{i,k} \geq \frac{1}{BW_{i,k}}$$

(28)

where $BW_{i,k}$ is the bandwidth of the filter in the receiver corresponding to the k^{th} antenna of the i^{th} MS.

- **<u>time delays, $\Delta t_{i,k}$:</u>**

The propagation delay $\tau_{i,k}$ is affected by $\Delta t_{i,k}$ which represents the system delay through antenna, cables, filters, amplifiers, etc. $\Delta t_{i,k}$ has to be estimated otherwise the propagation delay can be prolonged significantly.

- **<u>interference, $I_{i,k}(t)$:</u>**

Depending on the level of interference, $I_{i,k}(t)$ can have a drastic effect on the accuracy of the estimated phase and may saturate the RF front end of the receiver. Its effects can be mitigated with both analog and digital hardware, as well as adequate software, whether it is in-band or out-of-band.

- **<u>The effect of Multipath, $MP_{i,k}(t)$:</u>**

When multipath is considered, the accuracy of the IS-95 land-based WLS could potentially degrade beyond the 30m accuracy even with the required 8 samples per chip. The reason is that it is not always possible to resolve the multipath component from the direct path component when both components arrive within one chip from each other. The cellular frequency bands are in the mid-800MHz band and in the mid-1.9GHz band, and the propagation characteristics at these UHF frequencies will have a significant impact on positioning by multilateration as shown in Parsons D., "*The Mobile Radio Propagation Channel,*" John Wiley & Sons, New York, 1992. That the ranges measured correspond to Line Of Sight (LOS) distances is a major assumption made when estimating position by multilateration. Although the dominant transmission mode in this band is LOS, reflections from natural and man-made objects as well as diffraction around said objects are also possibilities. Multipath and diffraction allow the cellular signal to propagate in heavily built up areas as well as indoors. However, they also cause the measured ranges to be longer than the true LOS distance which introduces error into the multilateration process. In addition, the propagation distance at UHF is relatively short. This allows frequency reuse in the cellular system but limits the number of observables in the multilateration process. For instance, in a dense urban environment with a delay spread of 3 microseconds (as shown in Hata, M., "Empirical Formula for Radio Propagation Loss in Land Mobile Radio Services," *IEEE Transactions on Vehicular Technology,* Vol. VT-29, No. 3, August 1980) multipath causes the location accuracy to degrade. Once again, the reason for this is that the correlation function from which the multipath may be estimated has a resolution which is limited to that of the Fourier transform which implies that any multipath within such a resolution is unresolvable using traditional methods. Further processing using an inverse SR algorithm often yields a result with higher multipath resolution as shown by Dumont, L.R., et al., "Super-resolution of Multipath Channels in a Spread Spectrum Location System," *IEE Electronic Letters,*

Vol. 30, No. 19, pp. 1583-1584. September 15, 1994 and as shown by Fattouche et al., U.S. Patent No. 5,570,305 issued Oct., 1996, and as shown by Ziskind, I. et al., "Maximum Likelihood Localization of Multiple Sources by Alternating Projection," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. ASSP-36, No. 10, October, 1988. Another approach to multipath resolution is due to Morley, G.D. et al., "Improved Location Estimation with pulse-ranging in presence of shadowing and multipath excess-delay effects," *Electronics Letters*, Vol. 31, No. 18, pp. 1609-1610, 31st Aug., 1995.

4.3.3 Choices of p(t):

The choice of p(t) depends on the radio signal generated by the CT. Several standards are of interest to us such as CDMA, AMPs, TDMA, wideband CDMA, ESMR, two-way paging, etc.

4.3.3.1 CDMA Channels:

Regarding the types of CDMA channels to monitor, there are essentially two types: the access channels and the reverse traffic channels.

4.3.3.1.1 The Access Channels:

CDMA CTs may transmit messages on the Access channel when not communicating on a traffic channel. A CT may transmit on the Access channel in response to input from the CT user (such as dialing a call), in response to Paging messages received, or in response to other conditions (such as expiry of a registration timer).

Preamble and Capsule

An Access probe is a CT transmission consisting of a preamble and message capsule containing a complete message. The number of preamble and capsule frames in each access probe are determined by network configuration (PAM_SZ and MAX_CAP_SZ, respectively). A CT will transmit an Access probe (with identical message content) multiple times at varying power levels, until it receives a response from the cellular network or a specified number of probes have been transmitted.

<u>**Encoding and Modulation**</u>

The message types, structure, encoding, and modulation of the access capsule are described in the applicable CDMA standards (IS-95, J-STD-008). The bits comprising the message are processed with the following steps:

1. A message length (MSG_LENGTH in J-STD-008 section 2.7.1.2.1) field is prepended to the capsule message bits (J-STD-008 section 2.7.1.3).
2. A 30-bit CRC is computed and appended to the message length and message body fields (J-STD-008 section 2.7.1.2.2).
3. The capsule message bits are zero-padded to the maximum capsule length, which is $3 \times 88 \times (\mathrm{MAX\_CAP\_SZ} + 3)$.
4. The capsule bits are divided into frames of 88 information bits each.
5. An 8-bit encoder tail (zero-valued bits) is appended to each group of 88 bits.
6. Each frame of 96 bits is convolutionally encoded. The code rate is $1/3$ with a constraint length of 9, with generator functions $g_0 = 557$, $g_1 = 663$, and $g_2 = 771$ (all in octal). The encoder tail allows the shift registers to reset to zero-state between frames.
7. Each code symbol is repeated once, so that if the encoder output is (a, b, c, d,...) the repeated outputs are (a, a, b, b, c, c, d, d,...).
8. Each frame of code symbols is interleaved. Symbols are written by columns into an array of 32 rows by 18 columns. Symbols are read from the array by rows in this order: 1 17 9 25 5 21 13 29 3 19 11 27 7 23 15 31 2 18 10 26 6 22 14 30 4 20 12 28 8 24 16 32
9. The interleaved symbols are separated into groups of 6, and each group of 6 translated into a 64-chip Walsh code.

10. Each chip output from the previous stage is modulated by 4 chips from the long code (J-STD-008 section 2.1.3.1.8), which has a rate of 1.2288 Mcps. The long code mask, hence the long code phase, is determined by the network identification of the base station towards which the Access probe is directed.

11. The output from the previous stage is modulated by the I-channel and Q-channel short codes (J-STD-008 section 2.1.3.1.9).

12. The Q-channel signal is delayed by one-half of a chip, or 405.9 ns.

13. The I and Q-channel signals are converted into analog filters with a pulse-shaping function having specified properties (J-STD-008 section 2.1.3.1.10), and are upconverted to the appropriate frequency channel.

The preamble is generated by composing a frame of 88 zero-valued bits for each preamble frame, and applying steps 5-13 described above for the capsule bits. Note that since the preamble bits begin as zeros, steps 3-7 will have no effect beyond increasing the number of '0' bits or symbols. Thus, an alternative definition for the preamble content is a signal consisting of the long and short codes only. The deterministic nature of the preamble facilitates detection of the probe by receivers.

Slotted Transmission

Access probes are slotted. The slot width is the length of one access probe, which is determined by the network configuration (PAM_SZ and MAX_CAP_SZ). CDMA system time (which generally coincides with GPS time) is the time base for these slots.

PN Randomization

A CT will delay the transmission of an Access probe by a duration computed from a network configuration parameter (PROBE_PN_RAN) and the CT's ESN. The phases of the long and short codes applied to the probe are not affected by this delay. This delay will not affect TDOA positioning. For RTD positioning, a MS or host

must apply a correction for the PN Randomization delay to the measured TOA of an Access probe.

4.3.3.1.2 The Reverse Traffic Channels:

In most cases, CT transmissions on a Reverse Traffic channel will consist of the following stages:

1. The CT transmits the Reverse Traffic Preamble.
2. The CT transmits a mixture of null traffic and messages.
3. The CT transmits a mixture of voice traffic and messages.

The Reverse Traffic preamble consists of a datastream of all zeros modulated by the long and short codes only. The deterministic nature of this preamble aids in the acquisition of the reverse traffic signals by BSs and MSs. A CT transmits Reverse Traffic preamble frames upon initiating transmission on a Reverse Traffic channel, and continues to do so until an acknowledgment is received from a BS indicating successful acquisition of the preamble, or a time limit is reached.

In the second stage, following the preamble, the CT transmits message frames related to the negotiation of service options and in response to messages from the BS. The CT transmits null traffic frames when not transmitting message data.

In the third stage, the CT transmits variable-rate frames containing either messages or voice data.

MSs can detect Reverse Traffic transmissions from any of these three stages in order to locate the CT. In all cases, it is necessary for a MS to reconstruct the CT transmission in order to correlate with the received signal. A MS situated near a serving BS can decode Reverse Traffic frames and relay their content to other MSs, so that the other MSs may reconstruct the Reverse Traffic signal and detect it within their received signals.

4.3.3.2 AMPS Channels:

Regarding the types of AMPs channels to monitor, there are essentially two types: the reverse control channels and the reverse voice channels.

4.3.3.2.1 The Reverse Control Channels:

The reverse control channel is digital in nature and is therefore cyclo-stationary with a cycle corresponding to one half of a symbol (Manchester encoded).

4.3.3.2.2 The Reverse Voice Channels:

The reverse voice channel is analog in nature with inherent tones (the Supervisory Audio Tone (SAT), the Signaling Tones (ST) and harmonics of the pitch of the speech).

4.3.3.3 TDMA/GSM Channels:

Regarding the types of TDMA/GSM signals to monitor, there are essentially two types: the reverse digital control signals and the reverse digital traffic signals. Both signals are digital in nature and therefore are cyclo-stationary with a cycle corresponding to one information symbol. Both signals can therefore be used to generate tones at given frequencies after performing a nonlinear operation on them.

4.3.3.4 Wideband CDMA Channels:

For wideband CDMA, p(t) is selected from a family of finite-duration Pseudo-Noise sequences that have good autocorrelation properties and good crosscorrelation properties. The PN sequences are used to spread the information sequence and therefore p(t) is inherently cyclo-stationary with a cycle corresponding to the duration of one PN sequence. Suggested bandwidths are 5MHz, 10MHz and 15MHz. The practical description of the patent will describe methods and apparatus to estimate $\tau_{i,k}$ and to mitigate its sources of errors.

4.4 FOA:

4.1 $f_{i,k}$:

In the kinematic case where the CT moves with respect to the MSs, the speed and Direction Of Travel (DOT) of the CT may be of interest. The only source of information one can use to extract an independent equation for the speed and DOT of the CT is

$$f_{i,k} = \delta f_{i,k} - \Delta f_{i,k} + \Delta f_o \qquad (34)$$

which can be used to estimate the Doppler shift $\delta f_{i,k}$. This is explained in Figure 6 which assumes a three antenna system: the m^{th} antenna at MS_1 with coordinates $(x_{1,m},y_{1,m},z_{1,m})$, the k^{th} antenna at MS_2 with coordinates $(x_{2,k},y_{2,k},z_{2,k})$ and the n^{th} antenna of MS_3 with coordinates $(x_{3,n},y_{3,n},z_{3,n})$. In this case, the FOAs: $f_{1,m}$, $f_{2,k}$ and $f_{3,n}$ are related

- to the Direction Of Travel (DOT), φ, relative to Northing (clockwise),
- to the speed of travel, v, and
- to the frequency offsets $\Delta f_{i,k}$, as follows:

$$f_{1,m} = \delta f_{1,m} - \Delta f_{1,m} + \Delta f_o = v/\lambda \cos(\varphi-\Lambda_{1,m}) - \Delta f_{1,m} + \Delta f_o$$

(35a)

$$f_{2,k} = \delta f_{2,k} - \Delta f_{2,k} + \Delta f_o = v/\lambda \cos(\varphi-\Lambda_{2,k}) - \Delta f_{2,k} + \Delta f_o$$

(35b)

$$f_{3,n} = \delta f_{3,n} - \Delta f_{3,n} + \Delta f_o = v/\lambda \cos(\varphi-\Lambda_{3,n}) - \Delta f_{3,n} + \Delta f_o$$

(35c)

where

- $\Lambda_{1,m}$ is the clockwise angle from Northing to the line formed by $(x_{1,m},y_{1,m})$ and (x,y).
- $\Lambda_{2,k}$ is the clockwise angle from Northing to the line formed by $(x_{2,k},y_{2,k})$ and (x,y),

- $\Lambda_{3,n}$ is the clockwise angle from Northing to the line formed by $(x_{3,n}, y_{3,n})$ and (x,y), and
- (x,y) are the 2-D (horizontal) coordinates of the CT.

In other words, there are three equations (35a, b and c) with 6 unknowns: φ, v, $\Delta f_{1,m}$, $\Delta f_{2,k}$, $\Delta f_{3,n}$ and Δf_o. This is a problem that can be resolved if the frequency offsets $\Delta f_{i,k}$ are made equal to one another, i.e.

if $\Delta f_{1,m} = \Delta f_{2,k} = \Delta f_{3,n} = \Delta f$.

In this case, we have two equations with two unknowns: v and φ after using Frequency Difference Of Arrival (FDOA):

$$-f_{1,m} + f_{2,k} = v/\lambda \cos(\varphi - \Lambda_{1,m}) - v/\lambda \cos(\varphi - \Lambda_{2,k}) \quad (36a)$$

$$-f_{2,k} + f_{3,n} = v/\lambda \cos(\varphi - \Lambda_{2,k}) - v/\lambda \cos(\varphi - \Lambda_{3,n}) \quad (36b)$$

We refer to such a solution as **Solution V**. Note that in **Solution V** the position of the CT (x,y) must be known (or estimated) prior to estimating the speed and velocity of the CT, in order to be able to know $\Lambda_{1,m}$, $\Lambda_{2,k}$ and $\Lambda_{3,n}$ in equations (36).

In processing $f_{i,k}$ to estimate $\delta f_{i,k}$, we have the following sources of errors:

- <u>**noise, $w_{i,k}(t)$:**</u>

The Cramer-Rao Lower Bound provides a lower bound on the effect of AWGN on the variance, $\mathrm{var}(\delta\hat{f}_{i,k})\big|_{\mathrm{Tone}}$, of the estimate of the frequency δf_i of a tone:

$$\mathrm{var}(\delta\hat{f}_{i,k})\Big|_{\mathrm{Tone}} \geq \frac{12}{\mathrm{SNR}_{i,k}\big|_{\mathrm{Tone}} \times N_{i,k} \times (N_{i,k}^{2} - 1) \times 4\pi^{2}}$$

(37)

where

- $\mathrm{var}(\delta\hat{f}_{i,k})\big|_{\mathrm{Tone}}$ is the variance of the estimate, $\delta\hat{f}_{i,k}$, of the frequency $\delta f_{i,k}$,
- $\mathrm{SNR}_{i,k}\big|_{\mathrm{Tone}} = A_{i,k}^{2}/(2\sigma_n^{2})$ is the SNR of the tone at the k^{th} antenna of the i^{th} MS,
- $A_{i,k}$ is the amplitude of the tone at the k^{th} antenna of the i^{th} MS,

- σ_n^2 is the noise variance, and
- $N_{i,k}$ is the number of samples (which is directly related to the observation interval $T_{i,k}$).

- **frequency offsets, $\Delta f_{i,k}$:**

  As mentioned above, there are three equations (35a-35c) with 6 unknowns: φ, v, $\Delta f_{1,m}$, $\Delta f_{2,k}$, $\Delta f_{3,n}$ and Δf_0. This problem can be resolved if the frequency offsets $\Delta f_{i,k}$ are either removed or made equal to one another, i.e. if $\Delta f_{1,m} = \Delta f_{2,k} = \Delta f_{3,n} = \Delta f$. It is more realistic to have $\Delta f_{1,m} = \Delta f_{2,k} = \Delta f_{3,n} = \Delta f$ than to estimate and remove the frequency offsets.

- **multipath, $MP_{i,k}(t)$:**

  The effect of the multipath, $MP_{i,k}(t)$, in this case is to add some Doppler shift to $\delta f_{i,k}$ due to dynamic (non-stationary) reflectors such as cars, buses, trucks, etc.

- **interference, $I_{i,k}(t)$:**

  In this case, $I_{i,k}(t)$ plays the same role in distorting the estimate of the frequency $\delta f_{i,k}$ as in distorting the estimate of the phase $\zeta_{i,k}$ except that its effect can be reduced more significantly.

- **Error in Estimating (x,y):**

  In equations (36) it is assumed that the position, (x,y), of the CT is known prior to estimating its speed and DOT. This is usually not true and (x,y) needs to be estimated first. The estimation of (x,y) is imperfect, implying that it will contain errors that can affect the estimation of the speed of the CT and its DOT. The practical description of the patent will describe methods and apparatus to estimate $\delta f_{1,m}$, $\delta f_{2,k}$ and $\delta f_{3,n}$ and to mitigate its sources of errors.

4.5 Combination of $SOA_{i,k}$ and $\psi_{i,k}$:

Solution V: Maximum Likelihood Angle of Arrival Estimation (ML-AOA)

This section presents a unique means of estimating AOA of radio signals transmitted by a CT. This novel method addresses the problem of site-dependent variations in antenna gain and phase patterns.

4.5.1 Conventional Approach to AOA

This "conventional" approach to AOA is briefly described in order to highlight the differences in the novel approach to adaptive maximum likelihood AOA estimation.

4.5.1.1 Estimating AOA from POA

The POA of a mobile transmission (assumed without loss of generality to be an Access probe in a CDMA system) is measured on two (or more) antenna elements. Their difference $\psi_{i,1}-\psi_{i,2}$ is computed. A closed-form solution for the AOA is evaluated using $\psi_{i,1}-\psi_{i,2}$ based on equation (12), the separation, $d_{i,1,2}$, between the two antennas, and the wavelength, λ, of the radio signal. There may be multiple solutions. The solution(s) for AOA are incorporated with other information and algorithms, such as least-squares and sector information, in order to arrive at an estimate of position.

4.5.1.2 Estimating AOA from SOA

As many antennas have a gain pattern which varies with the physical angle of arrival, the SOAs of CT transmissions measured at different antenna elements can be used alone or in conjunction with POA in order to estimate AOA. U.S. Patents 5,541,608 and 3,824,595 describe AOA measurement systems which incorporate both POA and SOA measurement.

4.5.2 Maximum Likelihood AOA

Maximum likelihood AOA begins in the same way as the conventional approach described above. The POA, $\psi_{i,k}$, and SOA, $SOA_{i,k}$, of the access probe is measured for each antenna element on which the probe can be detected. For a pair of antenna elements, the phase difference and gain difference, or SOA ratio, are computed.

$$\Delta\psi_{i,1,2} = \psi_{i,1} - \psi_{i,2} \qquad \Delta SOA_{i,1,2} = \frac{SOA_{i,1}}{SOA_{i,2}}$$

For the phase difference $\Delta\psi_{i,1,2}$, we can construct $p_{\gamma_i}(\gamma_i \mid \Delta\psi_{i,1,2})$, a likelihood function for γ_i, the AOA at the i^{th} MS. If the conventional closed-form solutions for γ_i were 30° and 150° then the likelihood function would probably look something like Fig.10.

As long as the model of the conventional method is accurate, the likelihood function by itself does not really give us more information than the closed-form solution for AOA. The benefit of the maximum likelihood method is accrued in the combining of POA/SOA information, in its flexibility in accommodating real-world variations from the conventional model, and in the ease of adaptive training, as described in the following.

Suppose that in addition to $p_{\gamma_i}(\gamma_i \mid \Delta\psi_{i,1,2})$, we also construct $p_{\gamma_i}(\gamma_i \mid \Delta SOA_{i,1,2})$, the likelihood function of AOA at the i^{th} MS given the observed relative signal strengths measured on antennas: $antenna_1$ and $antenna_2$. In this case, suppose that these two antennas are from different sectors, and that Figs. 10 and 11 illustrate the likelihood functions $p_{\gamma_i}(\gamma_i \mid \Delta\psi_{i,1,2})$ and $p_{\gamma_i}(\gamma_i \mid \Delta SOA_{i,1,2})$ respectively. Qualitatively, $p_{\gamma_i}(\gamma_i \mid \Delta\psi_{i,1,2})$ and $p_{\gamma_i}(\gamma_i \mid \Delta SOA_{i,1,2})$ indicate that the AOA is probably very close to 30° or 150°. $p_{\gamma_i}(\gamma_i \mid \Delta SOA_{i,1,2})$ indicates that the AOA is probably from about 0° to 45°. It is apparent that a good estimate for the AOA is then 30°.

Some sort of monotonic combining function is required to combine the two likelihood functions. Multiplication is intuitively satisfying because of the relationship for independent joint probability:

$$p_{\gamma_i}(\gamma_i \mid \Delta\psi_{i,1,2}, \Delta SOA_{i,1,2}) = p_{\gamma_i}(\gamma_i \mid \Delta\psi_{i,1,2}) p_{\gamma_i}(\gamma_i \mid \Delta SOA_{i,1,2}).$$

although this is not necessarily applicable since the POA and SOA differences are not necessarily independent. Other possibilities include addition (x+y) or more complex functions (such as $x^2 + 10xy + y^2$).

In effect, we are approximating the joint conditional pdf/likelihood function $p_{\gamma_i}(\gamma_i \mid \Delta\psi_{i,1,2}, \Delta SOA_{i,1,2})$ by combining $p_{\gamma_i}(\gamma_i \mid \Delta\psi_{i,1,2})$ and $p_{\gamma_i}(\gamma_i \mid \Delta SOA_{i,1,2})$. A alternative approach is to somehow obtain and use the joint conditional pdf/likelihood function $p_{\gamma_i}(\gamma_i \mid \Delta\psi_{i,1,2}, \Delta SOA_{i,1,2})$.

Once the likelihood function for γ_i is synthesized from the available observations, γ_i can be estimated by the first moment of the distribution (the mean), the ordinate of the maximum of the distribution, or by some other appropriate means. Various measures of spread, such as the standard deviation of the distribution, can be used as measures of confidence in the estimate. In general, the less the spread of the distribution, the greater the confidence.

This method requires that we somehow obtain the likelihood functions. While we could construct the functions based on expressions for AOA, the distance between antennas, antenna phase patterns, and antenna gain patterns, the resulting model would be quite sensitive to errors or changes in the measured parameters. It is desirable to adopt some kind of adaptive or self-training approach.

Figure 12 illustrates the high-level steps involved in ML-AOA (Maximum Likelihood Angle of Arrival estimation).

Adaptive Training

The likelihood functions may be constructed by collecting known AOAs along with accompanying POAs and SOAs. These known AOAs may be computed from CT locations previously known, or measured by other means such as

- Global Positioning System (GPS);
- the "Russian GPS" system; and

- TDOA location by the WLS.

The WLS constructs the likelihood function $p_{\gamma_i}(\gamma_i \mid \Delta\psi_{i,1,2})$ by defining bins covering the expected ranges γ_i and $\Delta\psi_{i,1,2}$. When a CT transmission is detected with known γ_i and measured $\Delta\psi_{i,1,2}$, the bin whose range includes $(\gamma_i, \Delta\psi_{i,1,2})$ is incremented. Alternatively, that bin may be increased by a value related to the estimated confidence in γ_i and $\Delta\psi_{i,1,2}$. As this training procedure is repeated a sufficient number of times, the values in the bins will approximate $p_{\gamma_i}(\gamma_i \mid \Delta\psi_{i,1,2})$. The likelihood functions for SOA ratio, or for both POA and SOA, may be similarly constructed.

It may be desirable to apply additional processing, such as smoothing, to these empirical likelihood functions. Also, extra bins may be defined for each pair of antennas to count occurrences in which the CT transmission is detected at one antenna and not another.

The WLS will have opportunity to train not only from TDOA locations of E911 or fleet management services, but from all call originations on the CDMA carrier. When a WLS subsystem and host resources are idle, they can attempt to locate all call originations by TDOA. Any such location which is deemed sufficiently reliable can then be used to train the likelihood histograms.

The histograms may be initialized with estimates of the likelihood functions prior to training. The histograms may be smoothed by convolution with an appropriate smoothing function prior to use in estimation of AOA.

5. Positioning Technologies:

5.1 TOA/Range Positioning (Circular Multilateration)

In a 2-D (horizontal) location system it is possible to estimate the position of a CT from the range of the CT to at least two MSs. The CT horizontal position estimate is simply the intersection of two horizontal circles with radii equal to the

ranges and centered at the MSs. This method of positioning may therefore be called circular multilateration. Ranges may be calculated by subtracting the known time of transmission τ_0 of signal s(t) from the measured TOAs, $\tau_{i,k}$, of signal $r_{i,k}(t)$. There are three possible solutions:

1. When the Time of Transmission, τ_0, is known, we refer to the positioning technique as **Range positioning**.
2. When the time of transmission, τ_0, is unknown, and to be estimated, we refer to the positioning technique as **TOA positioning**.
3. When the time of transmission, τ_0, is unknown, and to be eliminated using TDOA, we refer to the positioning technique as **TDOA positioning** (which is discussed in the following two sections).

In Range positioning, one way of determining the time of transmission, τ_0, is to use the RTD between the BS transmission and the reception of the CT's response to the BS transmission. In this case, a minimum of two independent equations is required to solve for the two unknowns x and y.

In TOA positioning, there are now three unknowns: x, y and τ_0. TOAs from three MSs are required and the equation for the k^{th} antenna at the i^{th} MS is

$$\tau_{i,k} - \tau_0 - \frac{1}{c}\sqrt{\left(x - x_{i,k}\right)^2 + \left(y - y_{i,k}\right)^2} = 0 \qquad (38)$$

where

- $\tau_{i,k}$ is the Time Of Arrival of signal $r_{i,k}(t)$ at the k^{th} antenna of the i^{th} MS,
- τ_0 is the time of transmission of signal s(t) from the CT,
- (x, y) is the best known 2-D position of the CT,

- $(x_{i,k}, y_{i,k})$ is the known 2-D position of the k^{th} antenna at the i^{th} MS where $i=1, \ldots, N$.

When more than the minimum number of MSs, as explained above, are available, redundancy is said to exist. If a redundant set of measured TOAs contain errors, the TOAs must be adjusted in order to obtain a unique solution to the unknowns. The amount by which each TOA is adjusted is called the residual. Several methods of adjusting the observed TOAs such that the sum of the squares of the residuals is a minimum are available including: General Minimum Variance Unbiased Estimation, Best Linear Unbiased Estimation, Maximum Likelihood Estimation, Least Squares Estimation, Method of Moments, General Bayesian Estimation, Linear Bayesian Estimation, Kalman Filtering, etc. In this patent, a preferred embodiment of the method to adjust the observed TOAs such that the sum of the squares of the residuals is a minimum is Least Squares Estimation.

5.1.1 Effect of Geometry on TOA Positioning

In a location system, geometry (that is the relative positions of the MSs with respect to each other and the CT to be positioned) plays an important role as shown in equation (39)

$$\text{std(position)} = \text{DOP} \times \text{std}(\hat{R}_{i,k}) \tag{39}$$

where

- $\text{std}(\hat{R}_{i,k})$ is the standard deviation of the range estimate $\hat{R}_{i,k}$ obtained from equations (19) or (26), and
- DOP is Dilution Of Precision which is a measure of geometry.

In a 2-D location system, it is common to refer to the Horizontal DOP (HDOP) which is defined as

$$\mathrm{HDOP} = \sqrt{\mathrm{EDOP}^2 + \mathrm{NDOP}^2} \tag{40}$$

where

- EDOP is the East DOP and is defined as the square root of the element in the 1st row and 1st column of C_{TOA},
- NDOP is the North DOP and is defined as the square root of the element in the 2nd row and 2nd column of C_{TOA},
- C_{TOA} is an unscaled matrix defined as $C_{TOA} = \left[A^T C_l^{-1} A\right]^{-1}$,
- C_l is the unscaled measurement covariance matrix (the identity matrix of appropriate dimension),
- A is the design matrix for the model of equation (38) and is defined as

$$A = \frac{1}{c}\begin{bmatrix} -\dfrac{x - x_{1,k}}{d_{1,k}} & -\dfrac{y - y_{1,k}}{d_{1,k}} & -c \\ -\dfrac{x - x_{2,k}}{d_{2,k}} & -\dfrac{y - y_{2,k}}{d_{2,k}} & -c \\ \vdots & \vdots & \vdots \\ -\dfrac{x - x_{N,k}}{d_{N,k}} & -\dfrac{y - y_{N,k}}{d_{N,k}} & -c \end{bmatrix} \tag{41}$$

and $d_{i,k}$ is the best derived distance (range) between the CT and the k^{th} antenna at the i^{th} MS.

5.1.2 Weighting of the TOA Observations

In the position estimation process, not all TOA observations need carry the same weight. TOA observations thought to be more reliable may be weighted more heavily than those that are deemed less reliable. This is accomplished through the

observation covariance matrix. The inverse of C_l is the weight matrix. Larger values on the diagonal of C_l^{-1} correspond to heavier weighting for the corresponding TOA observations. In the context of cellular telephone positioning, RSSI at each MS is one method of assigning weights to the TOAs. A high RSSI at a MS implies a reliable TOA. This is due to two facts:

1. The RSSI at a MS usually consists of received signal power + received noise power. The noise in the receiver is mainly thermal noise which is a function of bandwidth and temperature. When two MSs have comparable temperatures and bandwidths, the received noise power is approximately the same in both MSs. Thus, a high RSSI implies a high received signal power, which in turn implies a high SNR. This is desirable.
2. Furthermore, a higher RSSI usually implies less shadowing than a lower RSSI, which in turn implies less multipath. This is also desirable.

5.1.3 Blunder Detection in TOA Positioning

Blunders are gross errors in the TOA observations. This can be caused by large signal level fluctuations due to either flat fading or sudden in-band interference. If unremoved, blunders cause large errors in the estimated position. It is possible to detect observations containing blunders by observing the misclosure of each observation during the iterative Least Squares process. Misclosure is defined as the value of the position model (38) given the best available position estimate (x, y). Observations containing blunders will generally have much larger misclosures than observations not containing blunders. When an observation is detected as having a blunder it may be removed from the position estimation process.

It is preferred to reduce the effect of geometry, i.e. reduce the value of HDOP in (40), by allowing a large number of MSs to monitor one CT. In cellular communications, frequency reuse and flat fading are common occurrences. Therefore, increasing the number of monitoring MSs (which probably reduces

HDOP) generally increases std($\hat{R}_{i,k}$). As a result blunder detection is crucial as part of the method of minimizing positional error by maximizing the number of MSs (and hence reducing HDOP) without incurring a large penalty on std($\hat{R}_{i,k}$). In cases where blunders are not detected, poor SNR at some MSs may cause the inclusion of measurements from those MSs to increase the std(range) more than they reduce HDOP. With this trade-off in mind, the invention optimizes the number of MSs used to locate the CT such that std(position) in (39) is minimized.

Blunders may also be detected by a statistical analysis of the observation residuals computed from the Least Squares process as shown by Vanicek, P., Krakiwsky, E., "*Geodesy: The Concepts*," North-Holland Publishing Company, Amsterdam, 1982. The residual of each TOA observation may be standardized by its own estimated standard deviation such that the entire set of residuals is assumed to belong to the normal distribution with zero mean and unit standard deviation. If this hypothesis is correct, the standardized residuals should fall within some specified confidence region for the standard normal distribution. An observation whose residual is flagged is suspected of containing a blunder.

5.2 TDOA Positioning (Hyperbolic Multilateration)

Instead of estimating the unknown time of transmission, it is possible to eliminate it. This is accomplished by differencing TOAs from two different MSs. Since the time of transmission is common to both it is eliminated from the resulting TDOA (Time Difference Of Arrival). It can be shown that the locus of points for which a particular TDOA is valid corresponds to a hyperbola. The side of the hyperbola on which the CT must lie is known by the sign of the TDOA. Given TOAs from three MSs, two independent TDOAs may be formed. The intersection of the two corresponding hyperbolas estimates the position of the CT. This method is commonly referred to as hyperbolic multilateration.

The 2-D positioning model for hyperbolic multilateration is

$$\Delta\tau_{ij,km} - \frac{1}{c}\sqrt{\left(x - x_{i,k}\right)^2 + \left(y - y_{i,k}\right)^2} + \frac{1}{c}\sqrt{\left(x - x_{j,m}\right)^2 + \left(y - y_{j,m}\right)^2} = 0$$

(42)

where

- $\Delta\tau_{ij,km} = \tau_{i,k} - \tau_{j,m}$, $i \neq j$ or $k \neq m$, and
- $\tau_{i,k}$ is the Time Of Arrival of signal $r_{i,k}(t)$ at the k^{th} antenna of the i^{th} MS.

5.2.1 Effect of Geometry on TDOA Positioning

Geometry affects TDOA positioning as well. The HDOP is again calculated from (40) where the design matrix is now

$$A = \frac{1}{c}\begin{bmatrix} -\frac{x - x_{2,m}}{d_{2,m}} + \frac{x - x_{1,k}}{d_{1,k}} & -\frac{y - y_{2,m}}{d_{2,m}} + \frac{y - y_{1,k}}{d_{1,k}} \\ -\frac{x - x_{3,n}}{d_{3,n}} + \frac{x - x_{1,k}}{d_{1,k}} & -\frac{y - y_{3,n}}{d_{3,n}} + \frac{y - y_{1,k}}{d_{1,k}} \\ \vdots & \vdots \\ -\frac{x - x_{N,l}}{d_{N,l}} + \frac{x - x_{1,k}}{d_{1,k}} & -\frac{y - y_{N,l}}{d_{N,l}} + \frac{y - y_{1,k}}{d_{1,k}} \end{bmatrix} \quad (43)$$

where N in (43) is the number of MSs. Note that the TOA at the k^{th} antenna of the first MS is subtracted from all other TOAs.

The unscaled observation covariance matrix is

$$C_l = \begin{bmatrix} 2 & 1 & \cdots & 1 \\ 1 & \ddots & 1 & \vdots \\ \vdots & 1 & \ddots & 1 \\ 1 & \cdots & 1 & 2 \end{bmatrix}. \quad (44)$$

5.2.2 Weighting of the TDOA Observations

Weighting of the TDOA observations is possible. However, because the TDOAs are a function of two TOAs, the method of assigning weights is no longer straightforward.

5.2.3 Blunder Detection in TDOA Positioning

Blunder detection may also be performed in TDOA positioning. However, in this context, misclosures and residuals correspond to TDOAs. Therefore, a failing misclosure or residual may be due to a blunder in either of the TOA observations from which the TDOA is derived. It is not always possible to isolate the offending MS.

5.2.4 Multiple Solutions in TDOA Positioning

Two hyperbola halves, formed from two independent TDOAs, may intersect twice. This results in two mathematically correct solutions. This is particularly true in the case of positioning CTs where short distances and poor geometry are commonplace.

Solution bifurcation (the existence of two solutions to the positioning equations) is most often a concern in the exactly determined case. For the exactly determined case, the existence of two solutions can be detected with the method given in Chaffee, J.W. et al., "Bifurcation of Pseudorange Equations," *Proceedings of the 1993 National Technical Meeting*, San Francisco, California, January 20-22, 1993, The Institute of Navigation. Although originally intended for the detection of bifurcation in the GPS (Global Positioning System), this method is equally applicable to the case of CT positioning.

When more than two TDOAs are available in the 2-D positioning case, the probability of exact solution bifurcation is extremely small. It is, however, possible

for bifurcation to exist for a subset of two TDOAs. In such a case, the second solution may affect the final solution obtained when using all available TDOAs.

In any case, when solution bifurcation exists, the iterative Least Squares position estimation algorithm may converge to either of the solutions. The solution converged to is a function of the initial starting position used to begin the iterative Least Squares process. To converge to the solution corresponding to the actual position of the CT, the initial position used to begin Least Squares must be relatively accurate. Given no a priori information about the location of the CT, a closed-form position estimation algorithm, using the TOA or TDOA observations, is the only choice.

A number of closed-form positioning algorithms have been developed. Examples are:

- spherical interpolation (Smith, J.O., et al., "Closed-Form Least-Squares Source Location Estimation from Range-Difference Measurements," *IEEE Transactions on Acoustics, Speech, and Signal Processing,* Vol. ASSP-35, No. 12, Dec. 1987, pp. 1661-1669),
- the method of Schau and Robinson (Schau, H.C., et al., "Passive source localization employing intersecting spherical surfaces from time-of-arrival differences," *IEEE Transactions on Acoustics, Speech, and Signal Processing,* Vol. ASSP-35, No. 8, Aug. 1987, pp. 1223-1225),
- Bancroft's method (Bancroft, S., "An algebraic solution of the GPS equations," *IEEE Transactions on Aerospace and Electronic Systems.* Vol. AES-21, No. 7, Jan. 1985, pp. 56-59), the method of Chan and Ho (Chan, Y.T., et al., "A Simple and Efficient Estimator for Hyperbolic Location," *IEEE Transactions on Signal Processing,* Vol. 42, No. 8, Aug. 1994, pp. 1905-1915), and
- LOCA (Location On the Conic Axis) by Schmidt, R.O. "A New Approach to Geometry of Range Difference Location," *IEEE Transactions on Aerospace and Electronic Systems,* Vol. AES-8, No. 6, Nov. 1972, pp. 821-835.

LOCA is used in the preferred embodiment of the invention as it pertains to the precise location of mobile transmitters. LOCA is the mathematical dual of hyperbolic trilateration. The fundamental theorem of LOCA states that TOA differences for three MSs of known location yield a straight line of position. This straight line is the major axis of a conic. The three MSs lie on the conic and the CT, the location of which is being estimated, lies at one of the foci of the conic. In the case of redundancy and 3-D positioning, LOCA is expanded into Plane Intersection as shown by Schmidt, R.O., "A New Approach to Geometry of Range Difference Location," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-8, No. 6, Nov. 1972, pp. 821-835. Plane Intersection is equally applicable to the case of redundancy in 2-D positioning.

In LOCA, three conics are possible: an ellipse, hyperbola, or parabola. The conic of interest depends on the relative positions of the MSs and the CT to be positioned. Each of these conics has two foci (for the parabola one focus is at infinity) and therefore two possible solutions. In the case, of an ellipse, the correct focus is determined from the signs of the TDOAs. In the case of the parabola, the solution is obvious. When the conic is a hyperbola, however, the correct focus cannot be determined from the given TDOAs. Chaffee's method of bifurcation detection in Chaffee, J.W. et al., "Bifurcation of Pseudorange Equations," *Proceedings of the 1993 National technical Meeting*, San Francisco, California, January 20-22, 1993, The Institute of Navigation, will indicate bifurcation for the case of the hyperbola and no bifurcation for the cases of the ellipse and parabola. With four MSs, a second conic is obtained. The intersection of the major axes of the two conics is the CT position estimate. Hence, there is no ambiguity and bifurcation is, therefore, not of concern when using Plane Intersection in the presence of redundancy.

If the TOAs contain large errors, LOCA or Plane Intersection may give a very poor solution. When used as the initial position for Least Squares, this poor solution may cause Least Squares to diverge. In that case, the best available course of action may be to average the coordinates of the participating MSs and use that as the initial

position for Least Squares. Another alternative is to use the approximate coordinates of the MS with which the CT is communicating, as the initial position.

5.3 Hybrid TDOA Positioning (Circular Multilateration with TDOAs)

In some cases it is desirable, or even necessary, to use TDOAs as opposed to TOAs. However, as explained above, it is not always possible to isolate blunders when using TDOAs. It is possible, however, to construct a positioning model that uses TDOAs but gives residuals and misclosures for individual TOAs.

To do this, one MS is chosen as the reference. The assumption is then made that the TOA at the reference site is equal to the time of transmission, τ_0. From this point on, the development follows that of circular multilateration except that the TOA of the reference MS is subtracted from all TOAs (including that of the reference MS) instead subtracting the time of transmission. The positioning model is then

$$\Delta\tau_{i1,k1} + \frac{1}{c}R_u - \frac{1}{c}\sqrt{\left(x - x_{i,k}\right)^2 + \left(y - y_{i,k}\right)^2} = 0$$

(45)

where

- $\Delta\tau_{i1,k1} = \tau_{i,k} - \tau_{1,1}$, $i = 1, \cdots, N$ and
- R_u is the range from the reference (first) antenna of MS_1 to the position of the CT.

The model of (45) has the same structure as that of circular multilateration (equation(38)) except that the third unknown is R_u and not the time of transmission.

The model of (45) gives N observations, and therefore N residuals and misclosures, for N MSs. The N observations, however, are a 0 and N-1 TDOAs. The structure of the equations is that of TOA positioning whereas the observations are that of TDOA positioning. Hence, the name Hybrid TDOA Positioning.

5.3.1 Effect of Geometry on Hybrid TDOA Positioning

The design matrix for hybrid TDOA positioning is

$$A = \frac{1}{c}\begin{bmatrix} -\frac{x - x_{1,1}}{d_{1,1}} & -\frac{y - y_{1,1}}{d_{1,1}} & 1 \\ -\frac{x - x_{2,k}}{d_{2,k}} & -\frac{y - y_{2,k}}{d_{2,k}} & 1 \\ \vdots & \vdots & \vdots \\ -\frac{x - x_{N,m}}{d_{N,m}} & -\frac{y - y_{N,m}}{d_{N,m}} & 1 \end{bmatrix} \qquad (46)$$

Note that (46) is the same as (41) except for the third column which corresponds to the third unknown.

The unweighted and unscaled observation covariance matrix, C_l, is the same as that for TOA positioning, the identity matrix of dimension N.

DOPs may be calculated, as before, from $\left[A^T C_l^{-1} A\right]^{-1}$.

5.3.2 Weighting of the Hybrid TDOA Observations

Although the observations are, strictly speaking, TDOAs, they may be treated as observations corresponding to the individual MSs. That is, the first observation, which is always zero, may be viewed as the observation of the reference (or first) MS. The second observation, consisting of the TOA of the reference MS subtracted from the TOA of the second MS, is treated as the observation of the second MS, and so on. Therefore, the N diagonal elements of C_l may be weighted for the individual MSs.

5.3.3 Blunder Detection in Hybrid TDOA Positioning

In like manner, N independent misclosures and residuals, one for each MS, are available for analysis. Blunder detection may then be performed as in the case of TOA positioning and blunders in individual TOA observations may be detected.

5.3.4 Multiple Solutions in Hybrid TDOA Positioning

Since the observations used are actually TDOAs, this method of positioning is subject to solution bifurcation. The method of dealing with multiple solutions discussed under hyperbolic multilateration is equally applicable here.

5.4 AOA Positioning:

Given unambiguous AOA measurements, only two unknowns exist for position estimation - the 2-D coordinates of the CT to be positioned. Therefore, a minimum of two independent AOA measurements are required. Again let (x, y) be the 2-D coordinates of the CT and $(x_{i,k}, y_{i,k})$ the 2-D coordinates of the k^{th} antenna of the i^{th} MS. At the k^{th} antenna of the i^{th} MS, the AOA, $\Lambda_{i,k}$, is measured, where: $\Lambda_{i,k}$ is the clockwise angle from Northing to the line joining the CT to the kth antenna of the ith MS (similar to $\Lambda_{i,k}$ in equations (35) and (36); not to be confused with $\gamma_{i,k}$ in equations (15), (16), (21), (22) and (23)).

The mathematical positioning model is then

$$(x - x_{i,k})\cos\Lambda_{i,k} - (y - y_{i,k})\sin\Lambda_{i,k} = 0 \tag{47}$$

When more than two independent AOA observations are available, Least Squares may be used to obtain a unique solution. We may assume that $\Lambda_{i,1} \cong \Lambda_{i,2} \cong \cdots \cong \Lambda_i$, i.e. that the CT is far from the i^{th} MS with respect to the baseline between all antennas at the i^{th} MS, and that the ranges $R_{i,1} \cong R_{i,2} \cong \cdots \cong R_i$.

5.4.1 Effect of Geometry on AOA Positioning

The relative positions of MSs with respect to each other and the CT to be positioned are also important for AOA positioning. DOP may again be used to quantify geometry. From the 2-D positioning model (47), the design matrix is found to be

$$A = \begin{bmatrix} \cos\Lambda_1 & -\sin\Lambda_1 \\ \cos\Lambda_2 & -\sin\Lambda_2 \\ \vdots & \vdots \\ \cos\Lambda_N & -\sin\Lambda_N \end{bmatrix} \tag{48}$$

The unscaled and unweighted observation covariance matrix, C_l, is the identity matrix of dimension N. The DOPs can again be found from $\left[A^T C_l^{-1} A\right]^{-1}$.

5.4.2 Weighting of the AOA Observations

The individual AOA observations may be weighted through the observation covariance matrix C_l. Those AOA observations deemed more reliable are assigned a smaller variance, or conversely, a heavier weight.

5.4.3 Blunder Detection in AOA Positioning

As in the case of TOA or TDOA observations, AOA observations may contain blunders. When redundant observations are available, statistical testing of the observation residuals and misclosures may be used to detect observations which contain blunders.

As mentioned above, the AOA solution in equation (12) has an ambiguity problem which can be resolved either by using TDOA as well as AOA as explained in the next section, or using more than two antennas at the same MS. This is possible in sectorized cells since each sector has usually two diversity antennas. In other words, in a three sector cell a total of six antennas could be available.

When the diversity antennas are separated only vertically, the estimated AOA is the elevation angle. In this case, it is possible to use both diversity antennas since they are independent from each other, i.e. they offer independent observations. The simplest method to use both observations is by combining them using: selection combining, maximal ratio combining, co-phasing combining, equal gain combining, or other methods of combining.

5.5 AOA/TDOA Positioning:

Least Squares allows for the combination of different types of observations. In particular, it is possible to estimate 2-D position using both AOA observations and TDOA observations within a single Least Squares adjustment.

A combination of the two different observation types is particularly useful in situations where only two MSs are available for estimating the 2-D position of a CT. When two antennas at a particular MS are used to estimate the incoming signal AOA for that MS, numerous AOA ambiguities are possible as shown in equation (15). This is due both to the nature of AOA estimation with a 1-D linear array, and to the fact that the spacing between elements can be greater than one wavelength. Therefore, with two MSs and AOA observations only, many position solutions are possible and there is no way of determining which of the many solutions is correct.

If, however, TOA is also measured at each of the two MSs (maybe using $p(t - \tau_{i,k} + \tau_0 - \Delta t_{i,k})$ in equation (18)), a TDOA can be calculated. This TDOA corresponds to a hyperbola side which, in the absence of error, will cross through the intersection point of two of the many bearing lines derived from the ambiguous AOAs.

When the AOA and TDOA observations include error, no two bearing lines and the measured hyperbola side will exactly intersect. For the measured TDOA and any two particular AOAs, Least Squares will give the position solution which minimizes the sum of the squares of the residuals. Observation residuals are available since there are two unknowns, the 2-D coordinates, but three observations (2 AOAs and 1 TDOA).

In order to separate the correct AOA pair from the ambiguities, each AOA combination is combined with the TDOA observation in Least Squares. That combination of AOAs which results in the smallest sum of squares of residuals is chosen as correct. The corresponding position solution is used as the CT position estimate.

When combining AOA and TDOA observations in Least Squares, both the model for AOA positioning (47) and the model for TDOA positioning (42) are used.

Without loss of generality, the design matrix A for two AOA observations (one at each of two MSs) and one TDOA observation (for the same two MSs) is

$$A = \begin{bmatrix} \cos\Lambda_1 & -\sin\Lambda_1 \\ \cos\Lambda_2 & -\sin\Lambda_2 \\ -\frac{x-x_2}{d_2}+\frac{x-x_1}{d_1} & -\frac{y-y_2}{d_2}+\frac{y-y_1}{d_1} \end{bmatrix}$$

(49)

where d_i is the best derived distance between the CT and the i^{th} MS assuming that the CT is far from the MS such that $d_{i,1} \cong d_{i,2} \cong \cdots \cong d_i$, where $d_{i,k}$ is the best derived distance between the CT and the k^{th} antenna at the i^{th} MS for i=1, 2. Note that the first two rows correspond to the two AOA measurements whereas the third row corresponds to the TDOA measurement. The two columns correspond to the two unknowns, x and y. Additional AOA and TDOA measurements may be included by adding appropriate rows to (49). Note that the $1/c$ factor seen in (43) is missing in the TDOA measurement row of (49). This is done such that the units throughout A are dimensionless.

The misclosure vector, necessary for the Least Squares adjustment mechanism, merely consists of the misclosures of all observations. The misclosure vector corresponding to the design matrix of (49) is

$$w = \begin{bmatrix} (x-x_1)\cos\Lambda_1 - (y-y_1)\sin\Lambda_1 \\ (x-x_2)\cos\Lambda_2 - (y-y_2)\sin\Lambda_2 \\ c*\Delta\tau_{12} - \sqrt{(x-x_1)^2+(y-y_1)^2} + \sqrt{(x-x_2)^2+(y-y_2)^2} \end{bmatrix}$$

(50)

where

- $\Delta\tau_{1,2} = \tau_1 - \tau_2$, assuming that the CT is far from the ith MS such that $\tau_{i,1} \cong \tau_{i,2} \cong \cdots \cong \tau_i$ for i=1, 2 and that
- $x_{i,1} \cong x_{i,2} \cong \cdots \cong x_i$ and $y_{i,1} \cong y_{i,2} \cong \cdots \cong y_i$.

Since the AOA and TDOA observations are independent, the unscaled observation covariance matrix is the identity matrix of appropriate dimension (number of AOA observations plus the number of TDOA observations).

5.5.1 Effect of Geometry on AOA/TDOA Positioning

DOP may again be used to quantify geometry. The DOPs (HDOP, EDOP, NDOP) can be found from $\left[A^T C_l^{-1} A\right]^{-1}$ where A and C_l are defined immediately above.

5.5.2 Weighting of the AOA/TDOA Observations

The individual AOA and TDOA observations may be weighted through the observation covariance matrix C_l. Those AOA and/or TDOA observations deemed more reliable are assigned a smaller variance, or conversely, a heavier weight.

5.5.3 Blunder Detection in AOA/TDOA Positioning

Both the TDOA and AOA observations may contain blunders. Statistical testing of the observation residuals and misclosures may be used to detect observations which contain blunders.

5.6 AOA/Range Positioning:

If the time of transmission or round-trip delay is known, the range, $\hat{R}_i$, from the CT to the i^{th} MS is the observed parameter. In that case, AOA and TOA positioning may also be combined in order to estimate the position of the CT with as little as two MSs. (Note that when the two MSs are collocated, such as in a sectorized cellular system, then in fact only one BS is needed). Without loss of generality, the design matrix A for two AOA observations (one at each of two MSs) and two range observations (one for each of the same two MSs) is

$$A = \begin{bmatrix} \cos\Lambda_1 & -\sin\Lambda_1 \\ \cos\Lambda_2 & -\sin\Lambda_2 \\ -\dfrac{x - x_{1,k}}{d_{1,k}} & -\dfrac{y - y_{1,k}}{d_{1,k}} \\ -\dfrac{x - x_{2,k}}{d_{2,k}} & -\dfrac{y - y_{2,k}}{d_{2,k}} \end{bmatrix}. \tag{51}$$

The misclosure vector corresponding to this design matrix is

$$w = \begin{bmatrix} (x - x_1)\cos\Lambda_1 - (y - y_1)\sin\Lambda_1 \\ (x - x_2)\cos\Lambda_2 - (y - y_2)\sin\Lambda_2 \\ \hat{R}_1 - \sqrt{(x - x_1)^2 + (y - y_1)^2} \\ \hat{R}_2 - \sqrt{(x - x_2)^2 + (y - y_2)^2} \end{bmatrix} \tag{52}$$

Since the AOA and range observations are independent, the unscaled observation covariance matrix is the identity matrix of appropriate dimension (number of AOA observations plus the number of range observations).

5.6.1 Effect of Geometry on AOA/Range Positioning

DOP may again be used to quantify geometry. The DOPs (HDOP, EDOP, NDOP) can be found from $\left[A^T C_l^{-1} A\right]^{-1}$ where A and C_l are defined immediately above.

5.6.2 Weighting of the AOA/Range Observations

The individual AOA and range observations may be weighted through the observation covariance matrix C_l. Those AOA and/or range observations deemed more reliable are assigned a smaller variance, or conversely, a heavier weight.

5.6.3 Blunder Detection in AOA/Range Positioning

Both the AOA and range observations may contain blunders. Statistical testing of the observation residuals and misclosures may be used to detect observations which contain blunders.

5.7 Speed and Direction of Travel Estimation:

In a kinematic location system, the 3-D or 2-D location of the moving CT must be estimated at various epochs of time. In addition, the doppler shift of the signal arriving at each MS may be estimated as discussed earlier. The equations relating the frequency (including Doppler shift) of the arriving signal at the MS to the CT speed, DOT and frequency offset are given in equations (35).

The estimation model for speed and DOT is, therefore,

$$f_{i,k} - v/\lambda \cos(\varphi - \Lambda_{i,k}) + \Delta f - \Delta f_o = 0 \qquad (53)$$

where Δf, the frequency offset, is assumed to be equal for all MSs. Given that at any particular epoch the position of the CT (x, y) is estimated by one of the above methods, the angle $\Lambda_{i,k}$ in (53) may be calculated for each MS. In equation (53) then, the knowns are $f_{i,k}$, λ and $\Lambda_{i,k}$, (where $f_{i,k}$ is measured or observed), and v, φ, Δf and Δf_0 are the unknowns. Three MSs are required - the same number required to estimate the 2D CT position using TOA or TDOA positioning.

5.7.1 Effect of Geometry on Speed and Direction of Travel Estimation:

Geometry affects the estimation of speed and DOT as well. For instance, it is intuitively obvious that when the CT is traveling on a line perpendicular to the line connecting it and an MS, no information regarding the speed of the CT is available from observed data at that MS.

The design matrix for the model of (53) is

$$A = \begin{bmatrix} -\frac{\cos(\varphi - \Lambda_{1,k})}{\lambda} & \frac{v}{\lambda}\sin(\varphi - \Lambda_{1,k}) & -1 \\ -\frac{\cos(\varphi - \Lambda_{2,m})}{\lambda} & \frac{v}{\lambda}\sin(\varphi - \Lambda_{2,m}) & -1 \\ \vdots & \vdots & \vdots \\ -\frac{\cos(\varphi - \Lambda_{N,l})}{\lambda} & \frac{v}{\lambda}\sin(\varphi - \Lambda_{N,l}) & -1 \end{bmatrix}$$

(54)

The DOPs can again be found from $\left[A^T C_l^{-1} A\right]^{-1}$. In this case the DOPs will be speed DOP, direction of travel DOP, and frequency offset DOP. C_l is the unscaled and unweighted identity matrix of dimension N.

Inducement and Acquisition of CT Signals

A CDMA-CT may be located from observation of one or more MSs of one or more of the following types of transmissions: CT Access channel transmissions; CT Reverse Traffic channel transmissions; BS Forward Traffic channel transmissions; and CT message contents (on the Access or Reverse traffic channels).

Therefore, estimation of CT location requires the CT be involved in forward and/or reverse link transmissions. MSs may continually monitor and wait such call activity, or additional steps may be taken in order to induce call activity, as described in the following sections.

Locating a Designated CT

In this context, a designated CT is a CT for which the Host knows the phone number before the location procedure begins. This situation might arise in several applications such as in: fleet management; kidnapping/person tracking; safety/Mayday; pet tracking; and stolen vehicle/CT. There are two overall approaches to locating a designated CT: Using Access channel measurements, and/or Using Reverse Traffic channel measurements.

Procedures IA and **IB** are used to locate a known CT using Access channel measurements. **Procedures IIA** and **IIB** are used to locate a known CT using Reverse Traffic channel measurements.

Procedure IA: Locating a known CT using the Access Channel with stored information

1. The host initiates a call to the designated CT.
2. The host orders a number of MSs to store received reverse link signals in a circular buffer in random access memory. The MSs may also do so automatically by replacing outdated data with recently collected data in a continual fashion independently of the Host.
3. The host orders a number of MSs to process their stored received signals searching for an Access channel transmission from the designated CT.
4. One or more MSs successfully detect an Access channel transmission from the designated CT, and notify the host of their successful detection; the estimated TOA, FOA, SOA and/or POA of the received Access channel transmission; and the message content and encoding.
5. The host informs one or more MSs of the estimated TOA, FOA, SOA and/or POA of the received Access channel transmission, and the message content and encoding of the Access channel transmission of the designated CT.
6. All MSs informed in the previous step attempt again to detect the CT transmission, and inform the host of success or failure. The successful MS informs the host of the estimated TOA, FOA, SOA, and/or POA of the received Access channel transmission.
7. The host uses the information reported by the successful MSs to estimate the location of the designated CT.

Any step or steps of **Procedure IA** may be repeated as necessary to achieve or improve an estimate of the location information of the designated CT, i.e. an estimate of TOA, FOA, SOA, and/or POA.

The following steps may be used in **Procedure IA** to assist the host in determining which MSs are likely to detect the Access channel transmission of the designated CT:

3a. The host orders MSs to monitor for a particular (forward link) paging message to the designated CT, such as a Channel Assignment Message. (This message would typically be transmitted only by a BS engaged in communications with the designated CT).

3b. All MSs which successfully detect a forward link paging message to the designated CT inform the host of their successful detection of said message, and the message content.

Procedure IIA: <u>Locating a known CT using the Reverse Traffic Channel with stored information</u>

1. The host initiates a call to the designated CT.
2. The host orders a number of MSs to store received reverse link signals in a circular buffer in random access memory. The MSs may also do so automatically by replacing outdated data with recently collected data in a continual fashion independently of the Host.
3. The host orders a number of MSs to process their stored received signals searching for an Access channel transmission from the designated CT.
4. One or more MSs successfully detect an Access channel transmission from the designated CT, and notify the host of their successful detection, the message content and encoding.
5. The host orders one or more MSs to process their stored received signals searching for a Reverse Traffic Preamble from the designated CT.
6. All MSs ordered in the previous step attempt to detect the Reverse Traffic Preamble, and if successful, inform the host of the estimated TOA, FOA, SOA, and/or POA of the received Reverse Traffic Preamble.

7. All MSs which successfully detected detect the Reverse Traffic Preamble in the previous step:
   - demodulate the Reverse Traffic frames from the designated CT following the preamble; and
   - inform the Host of the estimated TOA, FOA, SOA and/or POA of the received Reverse Traffic Preamble, and the message content and encoding of the preamble and successive frames.
8. The host informs one or more MSs of the estimated TOA, FOA, SOA and/or POA of the received Reverse Traffic Preamble, and the message content and encoding of the Reverse Traffic Preamble and subsequent Reverse Traffic frames of the designated CT.
9. All MSs informed in the previous step attempt again to detect the CT transmission, and inform the host of success or failure. The successful MS informs the host of the estimated TOA, FOA, SOA, and/or POA of the received Reverse Traffic Preamble.
10. The host uses the information reported by the successful MSs to estimate the location of the designated CT.

Procedure IIA may be aided by a MS decoding the Channel Assignment message transmitted by a BS to the CT, in order to obtain the Frame Offset, which controls the timing of the Reverse traffic frames.

Procedures IA and **IIA** can be combined in order to attempt to locate a designated CT using both the Access and Reverse Traffic channels.

<u>**Procedure IB:** Locating a known CT using the Access Channel in real time</u>

1. The host initiates a call to the designated CT.
2. Simultaneously, the host orders a number of MSs to process the received reverse link signals in real time searching for an Access channel transmission from the designated CT.
3. One or more MSs successfully detect an Access channel transmission from the designated CT, and notify the host of their successful detection; the estimated

TOA, FOA, SOA and/or POA of the received Access channel transmission; and message content and encoding.

4. The host uses the information reported by the successful MSs to estimate the location of the designated CT.

Procedure IB may be repeated as necessary to achieve or improve an estimate of the location information of the designated CT, i.e. to improve the estimate of TOA. FOA, SOA, and/or POA of the received Access channel transmission.

The following steps may be used in **Procedure IB** to assist the host in determining which MSs are likely to detect the Access channel transmission of the designated CT:

3a. The host orders a number of MSs to process the forward link searching for a particular paging message to the designated CT, such as a Channel Assignment Message. This message would typically be transmitted only by a BS engaged in communications with the designated CT.

3b. All MSs which detect a forward link paging message to the designated CT inform the host of their successful detection of said message, and the message content.

<u>**Procedure IIB**: Locating a known CT using the Reverse Traffic Channel in real time</u>

1. The host initiates a call to the designated CT.
2. The host orders a number of MSs to process the received reverse link signals in real time searching for an Access channel transmission from the designated CT.
3. One or more MSs successfully detect an Access channel transmission from the designated CT, and attempt to detect the Reverse Traffic Preamble and inform the host of the estimated TOA, FOA, SOA, and/or POA of the received Reverse Traffic Preamble.
4. The host uses the information reported by the successful MSs to estimate the location of the designated CT.

Procedure IIB may be aided by a MS decoding the Channel Assignment message transmitted by a BS to the CT, in order to obtain the Frame Offset, which controls the timing of the Reverse Traffic frames.

Procedures IB and **IIB** can be combined in order to attempt to locate a designated CT using both the Access and Reverse Traffic channels.

<u>**Locating a CT that is Making a Call**</u>

In this section, procedures are described for estimating the location of a CT which is making a call. The Host may not know the identity of the CT before the procedure begins. It is assumed that the criterion which triggers the need for the CT to be located is one of the following:

- the CT has originated a call (useful in RF planning and in traffic monitoring applications);
- the dialed number in the CT's call origination matches a desired called number (useful in emmergency/911 calls and electronic yellow pages);
- the Electronic Serial Number (ESN) of the CT originating a call matches a desired ESN (useful in crime prevention and security applications); or
- the Mobile Identification Number (MIN) of the CT originating a call matches a desired MIN (useful in detecting fraudulent calls).

The main difference between procedures in this section and those for locating a known CT in the previous section is that in this section we assume that the CT originates the call.

Procedure IIIA and **IIIB** are used to locate a CT making a call using Access channel measurements. **Procedure IVA** and **IVB** are used to locate a CT making a call using Reverse Traffic channel measurements.

<u>**Procedure IIIA**: Locating a CT that is making a call, using the Access channel with stored information</u>

1. A number of MSs continually store the received reverse link signal in a circular buffer in random access memory, and process this stored signal searching for Access channel transmissions.

2. A CT makes a call by transmitting an origination message on the Access channel.
3. One or more MSs successfully detect an Access channel transmission from the designated CT, and notify the host of
   - their successful detection;
   - the estimated TOA, FOA, SOA and/or POA of the received Access channel transmission; and
   - message content and encoding.
4. The host determines from the message content (which identifies the CT and the called number) whether to proceed with locating the CT by executing the remainder of this procedure, or to abort it.
5. If the host has determined to proceed, it informs one or more MSs of the estimated TOA, FOA, SOA and/or POA of the received Access channel transmission, and the message content and encoding of the Access channel transmission of the CT.
6. All MSs informed in the previous step attempt again to detect the CT transmission, and inform the host of success or failure. The successful MS informs the host of the estimated TOA, FOA, SOA, and/or POA of the received Access channel transmission.
7. The host uses the information reported by the successful MSs to estimate the location of the designated CT.

This procedure can also be used to locate CTs, which transmit any Access channel message, including Registration messages. In this case, a dialed number will not be available in the message.

<u>**Procedure IVA**: Locating a CT that is making a call, using the Reverse Traffic channel with stored information</u>

1. A number of MSs continually store the received reverse link signal in a circular buffer in random access memory, and search this stored signal for Access channel transmissions.
2. A CT makes a call by transmitting an origination message on the Access channel.

3. One or more MSs successfully detect an Access channel transmission from the designated CT, and notify the host of:
   - their successful detection;
   - the estimated TOA, FOA, SOA, POA of the received Access channel transmission, and
   - message content and encoding.
4. The host determines from the message content (which identifies the CT and the called number) whether to proceed with locating the CT by executing the remainder of this procedure, or to abort the procedure.
5. If the host has determined to proceed, it orders one or more MSs to search for the Reverse Traffic Preamble transmitted by the CT, and provides these MSs with a range of times over which to search, an estimated frequency offset, and the encoding of the Reverse Traffic Preamble.
6. All MSs ordered in the previous step attempt to detect the Reverse Traffic Preamble, and if successful, inform the host of the estimated TOA, FOA, SOA, and/or POA of the received Reverse Traffic Preamble.
7. All MSs, which successfully detected Reverse Traffic Preamble in the previous step:
   - demodulate the received Reverse Traffic frames from the designated CT following the preamble; and
   - inform the Host of the estimated TOA, FOA, SOA and/or POA of the received Reverse Traffic Preamble, and the message content and encoding of the preamble and successive frames.
8. The host informs one or more MSs of the estimated TOA, FOA, SOA and/or POA of the received Reverse Traffic Preamble, and the message content and encoding of the Reverse Traffic Preamble and subsequent Reverse Traffic frames of the designated CT.
9. All MSs informed in the previous step attempt again to detect the CT transmission, and inform the host of success or failure. The successful MS

informs the host of the estimated TOA, FOA, SOA, and/or POA of the received Reverse Traffic Preamble.

10. The host uses the information reported by the successful MSs to estimate the location of the designated CT.

This procedure may be improved by the inclusion of the following steps to monitor forward link transmissions:

3a. A MS detects a Paging Channel message addressed to a particular CT, and notifies the host of the message timing and content.

3b. The host extracts from the Paging message content information useful in predicting or detecting subsequent CT transmissions, such as the ESN of the CT, and the assigned frame offset.

Procedures IIIA and **IVA** can be combined in order to attempt to locate a designated CT using both the Access and Reverse Traffic channels.

Procedure IIIB: Locating a CT that is making a call, using the Access channel in real time

1. A number of MSs continually process the received reverse link signal searching for Access channel transmissions.
2. A CT makes a call by transmitting an origination message on the Access channel.
3. One or more MSs successfully detect an Access channel transmission from the designated CT, and notify the host of
   - their successful detection;
   - the estimated TOA, FOA, SOA and/or POA of the received Access channel transmission; and
   - message content and encoding.
4. The host determines from the message content (which identifies the CT and the called number) whether to proceed with locating the CT by executing the remainder of this procedure, or to abort it.

5. If the host has determined to proceed, it uses the estimated TOA, FOA, SOA and/or POA of the received Access channel transmission, and the message content and encoding of the Access channel transmission of the CT to estimate the location of the designated CT.

This procedure can also be used to locate CTs, which transmit any Access channel message, including Registration messages. In this case, a dialed number will not be available in the message.

<u>**Procedure IVB**: Locating a CT that is making a call, using the Reverse Traffic channel in real time</u>

1. A number of MSs continually process the received reverse link signal searching for Access channel transmissions.
2. A CT makes a call by transmitting an origination message on the Access channel.
3. One or more MSs detect an Access channel transmission from the designated CT, and notify the host of:
   - their successful detection;
   - the estimated TOA, FOA, SOA and/or POA of the received Access channel transmission, and
   - message content and encoding.
4. The host determines from the message content (which identifies the CT and the called number) whether to proceed with locating the CT by executing the remainder of this procedure, or to abort it.
5. If the host has determined to proceed, it orders one or more MSs to process the Reverse Traffic signals transmitted by the designated CT, and provides these MSs with a range of times over which to search, an estimated frequency offset, and the encoding of the Reverse Traffic signals.
6. All MSs ordered in the previous step process the Reverse Traffic signals, and inform the host of the estimated TOA, FOA, SOA, and/or POA of the received Reverse Traffic signals.

7. The host uses the information reported by the MSs to estimate the location of the designated CT.

This procedure may be improved by the inclusion of the following steps to monitor forward link transmissions:

3c. A MS detects a Paging Channel message addressed to a particular CT, and notifies the host of the message timing and content.

3d. The host extracts from the Paging message content information useful in predicting or detecting subsequent CT transmissions, such as the ESN of the CT, and the assigned frame offset.

Procedures IIIB and **IVB** can be combined in order to attempt to locate a designated CT using both the Access and Reverse Traffic channels.

In order to reduce or avoid: Gain Imbalance; Phase Imbalance; Carrier Feed-through; and DC offset, and be able to use the same RF front end for all standards (analog or digital) over a fixed band; and reject out-of-band Interferers (e.g. paging, trunked radio, etc.) using digital filters in the Digital Signal Processor (DSP), it is desirable to use a linear IF-sampling receiver for the Reverse and Forward channels. The IF-sampling receiver at the i^{th} MS is designed to have high rejection, low group delay variation and good sensitivity.

<u>Design I:</u>

1. Initial rejection is achieved at RF using an RF Band Pass Filter (BPF) (802), followed by an RF amplifier (803) for good sensitivity. The output of said amplifier is passed through another RF BPF (804).
2. The RF signal is downconverted to the desired IF frequency by a mixer (805). The mixer is driven by a LO signal from the RF Synthesizer (812) which is in turn driven by a Frequency Reference (811). The Frequency Reference is preferably obtained from a stable source, such as a GPS receiver.

3. The IF signal, output from the Mixer (805), is amplified by a first IF amplifier (806), filtered by a BPF(807), and is amplified by a second IF amplifier (808).
4. The IF signal is sampled and converted to a digital signal by the A/D converter (809), and is then stored and/or further processed by the Digital Signal Processor (810).
5. Selection of a specific CDMA frequency channel is accomplished by programming the RF Synthesizer (812) and/or adjusting the frequency of the Frequency Reference (811) to obtain a LO frequency which will downconvert the desired CDMA channel frequency to the desired IF. The LO frequency is the difference of the CDMA channel frequency and the IF frequency. The RF BPFs (802, 803) are designed to have a passband encompassing all CDMA frequency channels which the hardware is designed to support. The IF BPF (806) is designed to have a passband width encompassing most or all of the CDMA channel bandwidth. The IF BPF will reject signals outside of the desired CDMA frequency channel.

The CDMA signal at the output of the A/D converter (809) may not be at baseband, but the baseband CDMA signal is recovered by subsequent digital operations.

In the preferred embodiment, the IF frequency has a value of $(2k+4)F_{chip}$ where k is a positive integer and F_{chip} is the IS-95 CDMA chip rate of 1.2288×10^6 Hz. The A/D is samples the IF signal at a rate of $8F_{chip}$, or 9.8304 MHz. Let $x(n)$ be the n^{th} output of the A/D converter. The in-phase, or "real" part of the CDMA baseband signal is given, at a sampling rate of $4F_{chip}$, by the sequence:

$$\mathrm{Re}\{\bar{r}_{i,k}(n)\} = (-1)^n x(2n)$$

The quadrature, or "imaginary" part of the CDMA baseband signal, is obtained by the following steps:

1. Let $x_1(n) = x(2n-1)$.
2. Form the sequence $x_2(n)$ by fractionally delaying $x_1(n)$ by one-half sample (see Timo I. Laakso, Vesa Välimäki, Matti Karjalainen, Unto K. Laine, "Splitting the Unit Delay," in IEEE Signal Processing Magazine, vol. 13, no. 1, pp. 30-60, January 1996). The required passband for the fractional delay filter is approximately $3\pi/5$ radians, based on the bandwidth of the IS-95 CDMA forward and reverse link signals.
3. The quadrature of "imaginary" part of the CDMA baseband signal is then given by the sequence:

$$\mathrm{Im}\{\tilde{r}_{i,k}(n)\} = (-1)^{n+1} x_2(n)$$

Estimation of CT Location

Estimation of AOA

The AOA may be estimated from using SOA and/or POA from two or more antennas as described above. ML-AOA estimation may use training from CT location estimated by TDOA along with accompanying POA and SOA measurements.

An AOA estimate is an estimate of the angular orientation of a ray (a line with a beginning point that extends indefinitely in one direction) originating at a MS and passing through the location of the CT (Figure 3). The point of intersection of two such AOA estimates forms an estimate of the location of the CT.

Alternatively, the intersection of one such line with another locus on which the CT lies forms an estimate of the location of the CT. Combinations of loci leading to a location estimate include: a hyperbola branch from TDOA and a line from AOA; a circle from RTD range and a line from AOA; and a circle from FGRE and a line from

AOA. A measure of confidence in each AOA estimate can be used to weight the contribution of the AOA estimate to the position estimate.

Estimation of Range by FGRE

The relationship between path loss and BS-CT range may be used to estimate the position of the CT. When the forward gain is below a certain threshold, the range of the CT may be estimated by a fixed value, which is fairly close to the BS. A preferred value for the threshold is 5% of the maximum forward gain, and a preferred value for the corresponding range is 5% of the cell radius.

A FGRE range estimate will typically be combined with an AOA estimate to produce an estimate of the CT location.

Estimation of CT Location by TOA/TDOA

If TOA of a CT transmission has been measured at three or more MSs, then the location of the CT may be estimated from these measurements. If two such TOA measurements are available, then a branch of a hyperbola is defined on which the CT lies. This, combined with an AOA estimate, can yield an estimate for the location of the CT.

Estimation of CT Location by Range

An estimate of the range between the CT and a BS defines a circle centered at the BS, with radius equal to the estimated range, on which the CT lies. A range estimate relative to a second BS defines a second circle, which will generally intersect the first circle at two points. Each of these points of intersection is a potential solution for the location of the CT. If no other information (such as an additional range or and AOA estimate) is available, then the midpoint of the two solutions may be used as the estimate for the location of the CT.

Estimation of CT Location from Transmitted Messages

Under certain conditions, the CT will transmit messages whose content is useful in determining the location of the CT. In particular, the Pilot Strength Measurement

Message defined in IS-95A and J-STD-008 is transmitted by the CT and contains measurements of pilot signal strength or quality, and the TOA of pilot signals measured at the CT. IS-95B allows for similar information on pilot signal TOAs to be included in Access channel messages as well. Pilot TOA information may be used to estimate the location of the CT by the TOA/TDOA

Estimation of Mobile Location with Redundant Measurements

If more information is available than the minimum amount necessary to arrive at an estimate of the CT location, then there is redundant information available. Due to measurement error, the solutions for CT location arising from non-redundant subsets of the available information will generally differ. Weighted Least Squares, as described in this patent application, can effectively handle redundant measurements.

An alternative approach for dealing with redundancy across diverse types of measurements is to assign a weighting or confidence factor to each measurement. This confidence factor is an estimate of the accuracy of each measurement, and might typically be derived from the SOA and the type of measurement. For example, of two TOAs, the one with the higher SOA would be assigned a higher confidence factor than the other. A FGRE range estimate would be assigned a lower confidence estimate than most or all other methods due to the low reliability of FGRE. Measurements with the lowest confidence factors are removed, until the remaining measurements form a non-redundant set for estimating the CT location. Alternatively, measurements with the lowest confidence factors are removed until the remaining measurements can be processed together to estimate CT location with each measurement appropriately weighted by its confidence factor.

TOA Calibration

A wireless location system has to be calibrated prior to operation (and occasionally during operation) in order to remove the effect of the overall Group Delay, $\Delta t_{i,k}$, at each MS. Moreover, temperature and aging can cause the overall

Group Delay to change with time. Therefore, it is necessary to calibrate the system on a regular basis. A method to calibrate a wireless location system is as follows:

Procedure V:

1. calling a CT whose location is known to the Host;
2. monitoring the paging of the CT by a BS over the corresponding Paging channel using a MS;
3. monitoring the response of the phone to the page over the corresponding Access channel by the same MS;
4. notifying a plurality of MSs to monitor the signal $r_{i,k}(t)$ of the CT over the assigned Access channel during an observation time $T_{i,k}$; and
5. dropping the call; and
6. estimating the relative group delay between MSs by comparing the estimated location of the CT with the known location of the CT. The estimated location of the CT is based on the measured TDOAs of the CT signal.

Procedure V can be repeated a number of times in order to average the relative group delay over time.

Host Software

Given a number of positioning algorithms and a number of methods for blunder detection, the invention makes use of positioning strategy illustrated in Figures 9a, 9b, 9c and 9d for TOA/TDOA positioning. Figures 9 illustrate the preferred embodiment for adjusting the observed TOAs such that the sum of the squares of the residuals is a minimum. Other methods for adjusting the observed TOAs such that the sum of the squares of the residuals is a minimum are available including: General Minimum Variance Unbiased Estimation, Best Linear Unbiased Estimation, Maximum Likelihood Estimation, Method of Moments, General Bayesian Estimation, Linear Bayesian Estimation, Kalman Filtering, etc.

The TOA/TDOA positioning process begins with a set of TOA observations from a minimum of three MSs. If only three TOAs are available (901), solution bifurcation is tested for (902). In the event of solution bifurcation, the LOCA algorithm (903) is performed on the TOA observations yielding two solutions. These two solutions are each used as the initial position for Least Squares. (904 and 905) resulting in two Least Squares solutions for the CT. The Least Squares algorithm here, and in all other parts of Figure 9, is Hybrid TDOA positioning with received signal strength used to weight the individual MS observations. During every iteration of Least Squares, misclosures for each MS are calculated. If any misclosure exceeds some multiple of the RMS value of the entire set of misclosures, the corresponding MS, and its TOA, is no longer used within that particular execution of Least Squares.

If both Least Squares solutions (904 and 905) converge (906) but are not equal (907), it is assumed that Least Squares has converged to the two possible solutions and both Least Squares solutions are reported as possible positions for the CT (908). If the either of the LS solutions diverge (906) or the convergent solutions are equal (907), the two LOCA solutions from (903) are reported as possible positions of the CT (909).

If at (902) bifurcation is found to not exist, LOCA is again executed (910) but yields only one solution. This solution is used as the initial position in Least Squares (911).

When redundancy does exist (901), Plane Intersection (912) (or any other closed-form position estimation algorithm) is executed. The resulting solution is used as the initial position for Least Squares (913). At this point a check is made as to whether Least Squares (913 or 911) converged (914). If Least Squares converges, another check for observational redundancy is made (915). If there is no redundancy, the Least Squares solution is reported as the position estimate of the CT (923). If there is redundancy, the normalized residuals are statistically tested for normality (916). The Least Squares solution is reported (923) should all residuals pass. If any

residuals fail, the redundancy numbers of the failing observations are checked (917). The redundancy number of the i^{th} observation is defined as

$$g_i = \left(C_{\hat{r}} C_l^{-1}\right)_{ii} \tag{55}$$

where $C_{\hat{r}}$ is the covariance matrix of the residuals and is defined as

$$C_{\hat{r}} = C_l - A\left[A^T C_l^{-1} A\right]^{-1} A^T. \tag{56}$$

Should all failing observations have redundancy numbers less than some threshold (in the preferred embodiment of the invention, this threshold is 0.5), the Least Squares solution is reported as the CT position estimate (923).

If observations with failing residuals have redundancy numbers larger than the threshold (917), that observation with redundancy number greater than the threshold and with the largest standardized residual is permanently removed from the observation set (928). The initial position used for the previous execution of Least Squares is remembered (929) and used again in Least Squares with the truncated observation data set (930 or 931).

Should Least Squares now diverge (932), the previous Least Squares solution which did converge is reported as the position estimate of the CT (936). If Least Squares does converge (932), and there is no redundancy (933), the newly convergent Least Squares solution is reported (936). If there is redundancy (933), the standardized residuals are tested for normality (934). Should all the residuals pass, the newly convergent Least Squares solution is reported (936). Otherwise, if all failing observations have redundancy numbers less than some threshold (in the preferred embodiment of the invention, this threshold is 0.5), the newly convergent Least Squares solution is reported (936).

If observations with failing residuals have redundancy numbers larger than the threshold (935), that observation with redundancy number greater than the threshold and with the largest standardized residual is permanently removed from the observation set (928). The process then continues as described immediately above.

If at (914) Least Squares diverges, Least Squares is executed again but with the average of participating MSs coordinates used as the initial position (918). If Least Squares now converges (919) but there is no observation redundancy (920), the newly convergent Least Squares solution is reported as the position estimate of the CT (923). If there is redundancy (920), the standardized residuals are tested for normality (921). Should all residuals pass, the newly convergent Least Squares solution is reported (923). If some of the residuals fail but none of the corresponding observations have redundancy numbers greater than some threshold (922), the newly convergent Least Squares solution is reported (923).

If observations with failing residuals have redundancy numbers larger than the threshold (922), that observation with redundancy number greater than the threshold and with the largest standardized residual is permanently removed from the observation set (928). The process then continues from (928) as described above.

When Least Squares does not converge at (919), and there is no redundancy (924), either no solution is reported for this particular set of observation data or the solution from the last iteration before divergence is reported (927). If there is redundancy, but all of the standardized residuals pass the normality test (925), no solution is reported for this particular set of observation data or the solution from the last iteration before divergence is reported (927). Should some of the residuals fail, the observation with the largest standardized residual is permanently removed from the data set regardless of its redundancy number. The process then begins at point (912) as described above. Figures 9A-9D are also applicable for AOA positioning, AOA/TDOA positioning, and AOA/Range positioning.

Transferring Location Information of the CT over the Internet

Given that the Internet is global and inexpensive, the communication between the Host and the customer can be achieved over it. For example when a CT calls 911 for emergency, it is possible to relay the positional information of the CT from the Host to the PSAP over the Internet. Similarly, in the case when a powered-on CT is

to be located by a customer, its positional information can be relayed from the Host to the customer through the Internet.

The utility of the internet in its capacity of transferring CT location information on a global scale, extends the application of the wireless location system beyond the cellular network for which the MS's have been deployed. Through the latest Internet technology such as Java, JavaBeans, as well as CORBA (Common Object Request Broker Architecture), CT location information residing at the Host can be integrated with third-party information (i.e. a map database, or a database consisting of geo-coded business addresses such as restaurants, towing companies, etc.) residing in some other geographical location, perhaps even in another country. The combination of this CT location information with the third party information can be transferred over the Internet to allow customers to locate a particular CT wrt to either a map location (i.e. street address) and/or a business location, provided that the CT is within network coverage for the wireless location system. Through this process the CT location information and the third party database information can be accessed or "served up" to the customer through efficient Java Internet technology processes. The service provider will integrate together the various components including the CT location information derived from the wireless location system and the third-party information database. The integration process of the different databases is transparent to the customer. The customer will only know that the location-based service exists as such to bring all of the different components together to provide for a complete service which can be offered either on a regional, national or perhaps global basis. Through the internet these location-based services can now be offered on an economical basis to the customer. Examples of such services are fleet management, concierge services, roadside assistance, child find services, etc. Legality and security aspects are a concern on the Internet and a dedicated link might be sometimes necessary.

There will now be described an embodiment of the invention, incorporating maximum likelihood estimation, that uses downlink signals, and which may use signals from a single transmitter received by several antennas at the mobile transmitter. The same principles may be applied to maximum likelihood estimation using uplink signals.

The method of maximum likelihood estimation described herein in the case of AOA estimation takes advantage of the variation of signal strength with angle of arrival as shown in Fig. 20a and 20b for exemplary antennas A and B of Fig. 19. An idealized relationship between strength difference of arrival and angle of arrival is shown in Fig. 21. The effect of an obstruction is shown in Fig. 22, where a transmitter 2201 transmits to a multiple antenna receiver 2202. Ray 202 is the direct path, while the rays 201 and 203 constitute an indirect path reflecting off obstruction 2203. The detected signal in the case of the multipath situation of Fig. 5 may look like Fig. 23, where 501is the direct path, while 502 is the reflected path.

The hardware of the preferred embodiment of the invention consists of one or more IS-95 CDMA mobile phones 1803 operating within a network of IS-95 CDMA base stations 1801, modified in accordance with the description of the invention. Each base station 1801 typically transmits three separate pilot signals, differentiated by code phase, on three separate directional antennas 1802, as shown in Fig. 19, which are received by the receiver 1803. Fig. 20 shows directional antenna gain patterns that are typical of sectorized antennas for exemplary antennas 1802 shown in Fig. 19.

In addition, there is an FML-AOA computational unit that is connected to the IS-95 base station network by suitable communications links. An exemplary structure is shown in Fig. 14, with the communications links shown in bold lines. In the case of the FML-AOA embodiment, the host 1411 embodies the FML-AOA computational unit, which may be any of various hardware platforms programmed according to the description in this patent document. In the IS-95 network, mobile phones regularly

measure and report on pilot signal strengths. These reports are made available to the FML-AOA computational unit through its communications link.

The overall procedure for configuring, training, and estimating using FML-AOA is shown in Fig. 28. Overall, the procedure includes the steps of creating the distributions and setting all elements to zero (2801). Optionally, as described in more detail below, the distributions are initialized (2802). Next, the host waits until a signal strength measurement is reported (2803). If the angle of arrival is known, as for example determined by one of the precision location methods described in this patent document, then the angle of arrival and strength measurement pair is used to train the distribution (2804) and the system returns to the wait mode (2803). If the angle of arrival is not known, the system estimates the angle of arrival (2805) according to the method of maximum likelihood and returns to the wait mode (2803).

In the preferred embodiment, a two-dimensional SDOA-AOA likelihood distribution is defined for all possible pairs of transmitter antennas at a cellsite. For example, if a cellsite has three sectors (sector A, sector B, and sector G) with one transmit antenna each, then distributions would be defined for the following pairs:

D_AB for sector A and sector B,

D_BG for sector B and sector G, and

D_AG for sector A and sector G.

If a cellsite had six sectors, A, B, G, X, Y, and Z arranged in the order listed, then the distributions defined would be

D_AB for sector A and sector B,

D_BG for sector B and sector G,

D_GX for sector G and sector X,

D_XY for sector X and sector Y,

D_YZ for sector Y and sector Z, and

D_AZ for sector A and sector Z.

Depending on the sector orientations, sector widths, propagation environment, and sensitivity of signal measurements, the performance of FML-AOA may be enhanced by creating distributions for other sector pairs in addition to the adjacent pairs. Definition of distributions for excessive sector pairings should not significantly degrade estimation performance.

Each distribution is a two dimensional numeric array with dimensions (N_sdoa_bins, N_aoa_bins) as illustrated in Fig. 25. The elements are indexed from 0 to N_SDOA_bins-1 along the first (SDOA) dimension and from 0 to N_aoa_bins-1 along the second (AOA) dimension. These distributions may be implemented as a full array or as a sparse matrix structure, in which the indices and values of only nonzero values are stored. All elements of all distributions are initially set to zero.

Note that whenever an SDOA is computed as the difference of SOA for two particular sectors, one sector must always provide the minuend and the other must always provide the subtrahend. As the sign of the SDOA affects the estimation, the roles of subtrahend and minuend must not be exchanged in nor between training and estimation. The preferred means of maintaining this order is to assign a unique number to each sector in a cellsite, and to ensure that the sector with the lower number is always the minuend and the sector with the higher number is always the subtrahend. SDOA_low_bin should be assigned as a consequence of non-detection by the minuend antenna, and SDOA_high_bin should be assigned as a consequence of non-detection by the subtrahend antenna. Note that if detection is unsuccessful at both of a pair of antennas, then the distribution for that antenna pair is not included in training or estimation. Note that in the expression A - B = C, A is the minuend, B is the subtrahend, and C is the difference.

Each element of each distribution has an associated SDOA and AOA bin value, and an associated SDOA and AOA region which encompasses SDOA,AOA values within a certain neighbourhood of the bin value, as illustrated in Fig. 26. The value of the element serves as a measure of the likelihood of the associated region. The region associated with an element is defined as all (SDOA,AOA) points which

are closer to the associated (SDOA, AOA) value than to the (SDOA,AOA) values of all other elements.

The preferred measure of distance is |SDOA-SDOA(i)| + |AOA-AOA(i)|, where |x| refers to the absolute value of x. Many other useful definitions of distance may be used. Other implementations using regions of different sizes, possibly overlapping, and adapted to the nature of the observed data, may be used.

In the preferred embodiment, the associated SDOA values are linearly spaced (in dB) between low_sdoa_bin and high_sdoa_bin and the AOA values are linearly spaced between 0° and 360°.

The preferred values defining the SDOA-AOA distributions are

N_SDOA_bins = 41,
low_SDOA_BIN = -20 dB,
high_SDOA_bin = +20 dB, and
N_AOA_bins = 361.

Thus, the associated SDOA bin value for the SDOA-AOA distribution D(i,j) is

$$i \cdot \frac{(\text{high\_sdoa\_bin} - \text{low\_sdoa\_bin})}{\text{N\_sdoa\_bins} - 1} + \text{low\_sdoa\_bin}$$

and the associated AOA bin value for D_AB(i,j) is

$$j \cdot \frac{(360° - 0°)}{\text{N\_aoa\_bins} - 1} + 0° = \frac{j \cdot 360°}{\text{N\_aoa\_bins} - 1}$$

In the preferred embodiment, an observation (SDOA,AOA) consisting of a strength difference of arrival SDOA and an angle of arrival AOA is within the region associated with D(i,j) if all of the following four conditions are true, expect as stated in the accompanying exceptions.

condition 1: $\mathrm{SDOA} \geq \mathrm{SDOA\_low\_bin} + \left(i - \frac{1}{2}\right)\frac{(\mathrm{sdoa\_high\_bin} - \mathrm{sdoa\_low\_bin})}{\mathrm{N\_sdoa\_bins} - 1}$

exception 1: If i=0 then condition 1 is removed.

condition 2: $\mathrm{SDOA} < \mathrm{SDOA\_low\_bin} + \left(i + \frac{1}{2}\right)\frac{(\mathrm{sdoa\_high\_bin} - \mathrm{sdoa\_low\_bin})}{\mathrm{N\_sdoa\_bins} - 1}$

exception 2: If i=N_sdoa_bins-1 then condition 2 is removed.

condition 3: $\mathrm{AOA} \geq 0° + \left(i - \frac{1}{2}\right)\frac{(360° - 0°)}{\mathrm{N\_aoa\_bins} - 1}$

exception 3: If j=0 then condition 3 is removed.

condition 4: $\mathrm{AOA} < 0° + \left(i + \frac{1}{2}\right)\frac{(360° - 0°)}{\mathrm{N\_aoa\_bins} - 1}$

exception 4: If j=N_aoa_bins-1 then condition 4 is removed.

Given an observation of strength difference of arrival SDOA and angle of arrival AOA, the indices of the associated distribution element D_AB(i,j) may be determined by Procedure A1.

Procedure A1: Calculation of Distribution Indicies (i,j) for an Observed (SDOA, AOA)

step 1. Let i = the integer 0,1,2,...,(N_sdoa_bins-1) which is closest to

$$(\mathrm{SDOA} - \mathrm{SDOA\_low\_bin})\frac{\mathrm{N\_sdoa\_bins} - 1}{\mathrm{SDOA\_high\_bin} - \mathrm{SDOA\_low\_bin}}$$

step 2. Let j = the integer 0,1,2,...,(N_aoa_bins-1) which is closest to

$$\frac{(\mathrm{AOA})(\mathrm{N\_aoa\_bins} - 1)}{360°}$$

Procedure A2: Overall ML-AOA Training and Estimation

step 1. Select values for N_SDOA_bins, low_SDOA_bin, high_SDOA_bin, N_AOA_bins. The preferred values are 41, -20, 20, and 361, respectively.

step 2. Let N_sites be the number of cellsites in the region or network over which FML-AOA is implemented.

step 3. Let Site(i) represent the i^{th} cellsite in the region or network over which FML-AOA is implemented, $1 \le i \le$ N_sites.

step 4. For i = 1,2,...,N_sites execute step 5 and step 6.

step 5. For Site(i), select which pairs of transmitters will have SDOA-AOA distributions. The preferred embodiment selects all adjacent pairs of sectors.

step 6. Create SDOA-AOA distributions for all selected pairs of transmitters.

step 7. Optionally, initialize some or all the SDOA-AOA distributions which have been created. In the preferred embodiment, azimuth initialization is applied to all distributions (Procedure A3).

step 8. Each time a receiver reports a signal strength measurement from one or more transmitters, execute step 9 and step 10.

step 9. Attempt to determine the actual angle of arrival by means other than FML-AOA. Preferred means for doing so include network-based TDOA, GPS, and network-assisted GPS.

step 10. If the angle of arrival was determined in the previous step then train the SDOA-AOA distributions using Procedure A4, otherwise, estimate the AOA from one or more cellsites using Procedure A7. Return to step 8.

The receiver should try to detect and measure as many as possible signals in order to obtain as much training and estimation information as possible. These detection and measurement attempts may be entirely autonomous and/or as ordered

to do so by a central network control element. Said network control element may assign specific search parameters, such as which frequency or code channels, or code phase offsets to search in order to simplify or enhance the detection and measurement attempts of the receiver.

If a high-confidence position estimate can be obtained by use of FML-AOA alone or in conjunction with other means, the AOA can be computed for one or more receiver sites and said AOA along with SOA measurements can be used for FML-AOA training of receiver pairs not directly involved in obtaining the high-confidence position estimate.

Similarly, if a high-confidence AOA estimate can be obtained by use of FML-AOA alone or in conjunction with other means, the AOA can be computed for one or more receiver sites and said high-confidence AOA along with SOA measurements can be used for FML-AOA training of receiver pairs not directly involved in obtaining the high-confidence AOA estimate.

An optional step following the creation and zeroing of the distributions is an initialization of the distributions using the azimuths of the cellsite antennas, along with some fixed parameters. This initialization may be applied to some or all distributions of some or all cellsites. In the preferred embodiment, the azimuth initialization is applied to all distributions for which the azimuths of both antennas are known or can be estimated.

In the preferred embodiment, azimuth initialization models the SDOA-AOA distribution as a piecewise-linear relationship between two points determined by a fixed estimate of the peak SDOA and the azimuths of the two sector antennas. This results in two line segments, as shown in Fig. 27. The shorter of the two line segments is assumed to be on the front side of both antennas, and receives a heavier weighting than the other line segment. Other initializations based on the same concepts, such as various curves and distribution weightings, will be apparent to one of ordinary skill in the art.

The algorithm presented in Procedure A3 initializes the distribution D_AB, associated with the sector A antenna and the sector B antenna. In the preferred embodiment, this initialization is repeated for every distribution.

Procedure A3: Azimuth Initialization of a Distribution for Sectors A and B

step 1. Let D_AB represent the SDOA-AOA distribution for sectors A and B.

step 2. Select a value for the peak SDOA, S_0. The preferred value is 20 dB.

step 3. Select a value for the front side weighting, W_F. The preferred value is 10.

step 4. Select a value for the back side weight, W_B. The preferred value is 2.

step 5. Assign to θ_A the azimuth of the sector A antenna, and to θ_B the azimuth of the sector B antenna.

step 6. Compute i_low and j_low such that D_AB(i_low, j_low) is the element of D_AB whose region contains the SDOA, AOA pair $-S_0$, θ_B (see Procedure A1).

step 7. Compute i_high and j_high such that D_AB(i_high, j_high) is the element of D_AB whose region contains the SDOA, AOA pair S_0, θ_A (see Procedure A1).

step 8. Compute k=sgn(j_low-j_high), where sgn is the signum function.

step 9. If $|\theta_A - \theta_B| > 180°$ then let D1 = W_B and D2 = W_F.

step 10. If $|\theta_A - \theta_B| \leq 180°$ then let D1 = W_F, D2 = W_B.

step 11. Repeat steps 11 through 14 for i = i_low, i_low+1, i_low+2, ..., i_high

step 12. Let $j = \text{the integer closest to } j\_low + (i - i\_low)\dfrac{j\_high - j\_low}{i\_high - i\_low}$

step 13. Let D_SDOA(i,j)=D1

step 14. Let

$$j = \text{the integer closest to } j\_low + (i - i\_low)\frac{j\_high - j\_low + k(360^\circ)}{i\_high - i\_low}, \ \bmod 360^\circ$$

step 15. Let D_SDOA(i,j)=D2.

In the preferred embodiment, each SOA-AOA distribution is trained when a receiver at a known azimuth with respect to a transmitter site attempts to detect a transmission from the two transmitters associated with said distribution, and is successful in detecting and measuring the strength of arrival of the signal from at least one of the two transmitters.

There are various well-known means for determining the azimuth, including satellite location systems such as GPS, network-assisted GPS, trilateration using the time of arrival of transmissions from the mobile at cellsites, trilateration using the times of arrival of pilot signals at the mobile, and measurement of the AOA of transmissions from the mobile by RML-AOA, doppler, pseudo-doppler, or phased arrays.

There are various means for detecting the transmissions and measuring strength of arrival, including correlation and grouped coherent correlation as described in this patent document. Grouped coherent correlation is preferred. Factors which will affect the measurement of strength of arrival which are or can be known should be corrected, including receiver AGC and transmitted pilot signal strength. θ can be computed from the known location of the cellsite, and from a mobile position estimate obtained by any suitable means, including network-based TDOA, TDOA of forward pilot signals, and mobile-based GPS.

Procedure A4: FML-AOA Training for Multiple Cellsites

step 1. Let N_sites be the number of cellsites in the region or network over which FML-AOA is implemented.

step 2. Let Site(i) represent the ith cellsite in the region or network over which FML-AOA is implemented, $1 \leq i \leq N\_sites$.

step 3. For i = 1,2,...,N_sites execute step 4, step 5, and step 6.

step 4. Let N_sectors be the number of sectors at Site(i).

step 5. Let Sector(j) represent the jth sector of Site(i), $1 \leq j \leq N\_sectors$.

step 6. For j = 1,2,...,N_sectors-1 execute step 7.

step 7. For k = j+1,j+2,...,N_sectors-1 execute step 8.

step 8. If a FML-AOA distribution exists for the pair of sectors Sector(j) and Sector(k) then execute Procedure A5 to train the distribution for Sector(i) and Sector(j) using the known AOA, the detection of the transmission at Sector(i), if available, and the detection of the transmission at Sector(j), if available.

Procedure A5: Training of the FML-AOA distribution for a given pair of sectors

step 1. Let A be the first, and B the second of the two sectors corresponding to the distribution.

step 2. Let S_A be the strength of arrival, in dB, reported for sector A, and S_B the strength of arrival, in dB, reported for sector B.

step 3. Let AOA be the angle of arrival, expressed as an azimuth, of the receiver with respect to the transmitter site (cellsite).

step 4. If the signal from sector A was detected and the signal from sector B was detected, then compute SDOA = S_A - S_B.

step 5. If the signal from sector A was detected and the signal from sector B was not detected, then let SDOA = high_SDOA_bin.

step 6. If the signal from sector A was not detected and the signal from sector B was detected, then let SDOA = low_SDOA_bin.

step 7. If the signal from sector A was not detected and the signal from sector B was not detected, then omit step 8 and step 9.

step 8. Compute the distribution indicies i_SDOA and i_AOA such that the observation SDOA, AOA is within the region associated with the distribution element D_AB(i_SDOA, i_AOA). This may be done using Procedure A1.

step 9. Let D_AB(i_SDOA,i_AOA) = D_AB(i_SDOA,i_AOA)+1.

After many training iterations at varied AOAs, D_SDOA will form an empirical likelihood distribution of SDOA and AOA, which can be used to predict AOA from an observed SDOA.

In an alternative embodiment of the invention, distributions associated with antenna pairs are dynamically created in response to detection of transmissions for which the angle of arrival is known or determinable. In this case, steps 5 and 6 of Procedure A2 may be partially or completely omitted. Procedure A6 describes the preferred embodiment for training including dynamic creation of distributions. This procedure will create distributions as required in order to make full use of available signal information in order to estimate angle of arrival.

Procedure A6: Training of the FML-AOA distribution for a given pair of sectors with dynamic creation of distributions

step 1. Let N_sectors be the number of sectors at the cellsite.

step 2. Let Sector(i) represent the i[th] sector of the cellsite, $1 \le i \le N\_sectors$.

step 3. For i = 1, 2, 3,...,N_sectors-1 execute step 4.

step 4. For j = i+1, i+2,...,N_sectors execute step 5 and step 6.

step 5. If the transmission was detected on Sector(i) and Sector(j) and a distribution for that sector pair does not yet exist, then create a distribution for that pair, and optionally initialize it using Azimuth initialization (Procedure A3).

step 6. If the transmission was detected on one or both of Sector(i) and Sector(j) and a distribution for that sector pair exists, then execute Procedure A5 to train the distribution for Sector(i) and Sector(j), using the known AOA.

Procedure A7: Estimation of AOA by FML-AOA

step 1. Let N_sites be the number of cellsites in the region or network over which FML-AOA is implemented.

step 2. Let Site(i) represent the i^{th} cellsite in the region or network over which FML-AOA is implemented, $1 \leq i \leq$ N_sites.

step 3. For i = 1,2,...,N_sites execute the following steps.

step 4. Let S_P be the set of AOA likelihood distributions selected for Site(i). Initialize S_P to be the empty set.

step 5. Let N_sectors be the number of sectors at Site(i).

step 6. Let Sector(j) represent the jth sector of Site(i), $1 \leq j \leq$ N_sectors.

step 7. For j = 1,2,...,N_sectors-1 execute step 8.

step 8. For k = j+1,j+2,...,N_sectors execute step 9.

step 9. Execute step 10 through step 16 if and only if a FML-AOA distribution exists for the pair of sectors Sector(j) and Sector(k), and the signal from Sector(j) and/or Sector(k) was detected.

step 10. Let S_A be the strength of arrival, in dB, reported for Sector(j), and S_B the strength of arrival, in dB, reported for Sector(k).

step 11. If the signal from Sector(j) was detected and the signal from Sector(k) was detected, then compute SDOA = S_A - S_B.

step 12. If the signal from Sector(j) was detected and the signal from Sector(k) was not detected, then let SDOA = high_SDOA_bin.

step 13. If the signal from Sector(j) was not detected and the signal from Sector(k) was detected, then let SDOA = low_SDOA_bin.

step 14. Compute the distribution index i_SDOA corresponding to SDOA (using step 1 of Procedure A1).

step 15. Let P(n) = D(i_SDOA, n) for n=1,2,3,...,N_AOA_bins, where D is the currently selected SDOA-AOA distribution.

step 16. Add P(n) to S_P (the set of AOA likelihood distributions for Site(i)).

step 17. Denote the members of S_P,in any order, as P_1, P_2, P_3,..., P_{NP}, where NP is the number of AOA distributions in the set S_P.

step 18. Select a value for p_0. The preferred value is 2.

step 19. For n=0,1,2,...,N_AOA_bins-1 compute

$$P_{combined}(n) = \prod_{m=1}^{P_{NP}} (P_m(n) + p_0)$$

$$= (P_1(n) + p_0) \cdot (P_2(n) + p_0) \ldots (P_{NP}(n) + p_0)$$

step 20. Select a value for α, the weighting exponent. The preferred value is 1.5.

step 21. Compute $\hat{x} = \sum_{n=0}^{N\_AOA\_bins-1} P_{combined}(n)^{\alpha} \cos\left(\frac{n \cdot 360°}{N\_AOA\_bins - 1}\right)$,

where the cosine function takes its argument in degrees.

step 22. Compute $\hat{y} = \sum_{n=0}^{N\_AOA\_bins-1} P_{combined}(n)^{\alpha} \sin\left(\frac{n \cdot 360°}{N\_AOA\_bins - 1}\right)$,

where the sine function takes its argument in degrees.

step 23. Compute $\hat{\theta}$, the angle measured clockwise from the line segment from (0,0) to ($\hat{x}$, $\hat{y}$) and the x-axis. The estimated AOA for Site(i) is $\hat{\theta}$.

The parameter α varies the weighting of distribution values P(n) according to their magnitude. A value of α=1 yields the mean or first-order moment in the following equations. A higher value of α will increase the weighting of higher values of P(n) versus lower values. The preferred value is α=1.5.

The parameter p_0 serves to diminish the contribution of small amounts of training data (which are considered to be less reliable). p_0 also prevents empty bins in one distribution from completely nullifying the corresponding bin values in other selected distributions.

The step 19 is illustrated graphically in Figs. 24a, 24b and 24c for first and second SDOAs, where the probability distributions for the first SDOA (Fig. 24a) is multiplied by the probability distribution for the second SDOA (Fig. 24b) to yield a combined AOA likelihood distribution (Fig. 24c).

In an alternative preferred embodiment of Procedure A7, step 15 is augmented by applying smoothing to the SDOA-AOA distribution. Smoothing consists of summing weighted contributions of nearby elements of the SDOA-AOA distribution in order to obtain an AOA distribution for the observed SDOA. This smoothing

operation may be understood as a two-dimensional discrete convolution. The preferred smoothing filter is defined as follows:

h(-2,-2) = 1	h(-2,-1) = 2	h(-2,0) = 4	h(-2,1) = 2	h(-2,2,) = 1
h(-1,-2) = 2	h(-1,-1) = 4	h(-1,0) = 8	h(-1,1) = 4	h(-1,2) = 2
h(0,-2) = 4	h(-1,0) = 8	h(0,0) = 16	h(0,1) = 8	h(0,2) = 4
h(1,-2) = 2	h(-1,1) = 4	h(1,0) = 8	h(1,1) = 4	h(1,2) = 2
h(2,-2) = 1	h(-1,2) = 2	h(2,0) = 4	h(2,1) = 2	h(2,2) = 1

Step 15 of Procedure A7 is then revised to the following:

Let $P(n) = \sum_{k=-2}^{2} \sum_{m=-2}^{2} D(i\_SDOA - k, (n-m) \bmod N\_AOA\_bins) \cdot h(k,m)$ for n=1,2,3,...,N_AOA_bins, where D is the currently selected SDOA-AOA distribution, and any nonexistent values referenced in the double summation are interpreted as zero.

Many other suitable smoothing filters (typically lowpass filters) will be apparent to those skilled in the art. The limits of the double summation are adjusted to encompass the region over which the smoothing filter h(k,m) is defined.

FML-AOA may be implemented as previously described, but with the strength of arrival measurements (in dB) replaced with phase of arrival measurements. As well, FML-AOA may be implemented using both phase and SOA measurements, and combining all one-dimensional distributions $P_1(n)$, $P_2(n)$, $P_3(n)$,... as follows: $P(n) = (P_1(n) + p_0) \cdot (P_2(n) + p_0) \cdot (P_3(n) + p_0) \ldots$ DOA bins should range from 0 to 360 degrees.

There will now be described embodiments of the invention in which reverse link signals are used to locate a mobile transmitter, the emphasis being on use of maximum likelihood estimation to improve the accuracy of location estimates, and improved detection of mobile transmitter signals, particularly in reference to a CDMA system.

An exemplary MLR System is shown in Fig. 30. The main physical elements of the MLR system are

- the transmitter 3001,
- receivers 3002,
- the backhaul communications network 3003, and
- the MLR Host 3004.

The MLR system is used to determine or estimate the location of a transmitter. The system can determine the location of many transmitters in succession or in parallel.

The transmitter 3001 transmits a wireless signal having certain properties which allow this signal to be received, detected, and measured. In the preferred embodiment, the transmitter 3001 is a mobile station as defined by the IS-95 standard, and the transmission consists of an IS-95 Access Probe. Many other embodiments are possible, such as other types of wireless communications devices, including transmit-only devices.

Each receiver 3002 includes means for detecting and measuring a transmission from the transmitter. In the preferred embodiment, a receiver 3002 comprises a radio frequency antenna, a bandpass filter, a low-noise amplifier, a frequency downconverter, an analog to digital sampler, and a digital processor. A number of suitable receiver basic hardware implementations are well known by those or ordinary skill in the art.

There are two techniques which are particularly applicable to the receiver 3002 which bear mention as they are not known in the art: (1) grouped coherent combining, and (2) the secondary search method, both of which are described in this

patent document and may be incorporated in the digital processor of the receiver 3002, as for example with software prepared according to the description in this patent document. These two techniques, applied either jointly or independently, are useful for increasing the effectiveness of signal detection with limited signal processing resources.

Note that groups of receivers may be located closely together, as in sectors of a cellsite. In this case, each sector would correspond to a receiver. If a sector has more than one antenna for diversity reception, then each antenna can correspond to a receiver.

The preferred method by which receivers attempt to detect and measure a potential received transmission is to correlate the actual received signal with a reconstruction of part or all of the expected signal. The expected signal may be a preamble in IS-95 access channel, a replica of which may be stored at the receiver 3002. Frequency offset in the received signal may arise due to doppler effects and frequency errors. In order to avoid a significant degradation when correlating signals longer than about one quarter of the reciprocal of the possible frequency error, the correlation can be computed at a variety of frequency offsets. Grouped coherent combining, as described in the description of the invention at section 2.4.3, is a computationally efficient means of correlating the signals at a variety of frequency offsets. The preferred spacing of these frequency offsets is one half of the reciprocal of the duration over which signals are correlated. The two signals are correlated in small segments, and the results of these small correlations are superimposed with the various frequency offsets. The preferred duration of the small segments is at most one quarter of the reciprocal of the largest frequency offset anticipated.

A summary of the procedure is shown in Fig. 13A, and includes the following steps:

1303 - sample received signal to obtain $\tilde{r}_{i,k}(m-\tau/T_s)$

1304 - reconstruct the transmitted baseband signal $p(mT_s)$

1305 - compute subcorrelations $c(n,\tau)$

1306 - compute correlation values $z_3(\tau,F)$ using grouped coherent combining, over trial values τ_i and F_j (using the equation set out in section s. 2.4.3).

1307 - Find maximum of $z(\tau_i,F_j)$, denote corresponding ordinates as $(\hat{\tau},\hat{F})$.

The secondary search method involves the following elements:

- a set of receivers called the primary search set, for example receivers 2, 3 in Fig. 30
- a set of receivers called the secondary search set, for example receivers 4, 5 in Fig. 30
- a transmitter, for example transmitter 3001
- the Host, a central processing and decision making entity, for example Host 3004 and
- means of communications between the Host and each of the receivers in the primary and secondary sets (for example the backhaul network 3003).

The primary set of receivers, with limited or no prior knowledge of the transmission, monitor their respective received signals so as to reliably detect a transmission if one occurs, with small probability of deciding in error that a transmission has occurred. The overall process is illustrated in Fig. 31.

A transmitter transmits a transmission at 3101, 3102, which is called the target transmission, which may include for example a preamble in an access channel.

One or more receivers in the primary search set detect said transmission. Each receiver which detects the target transmission extracts relevant information from the transmission by measuring the TOA, FOA, SOA, and POA of the transmission, and possibly decoding a message in the transmission.

Each receiver in the primary search set which detected the target transmission composes a message containing the information extracted from the target transmission (3103). This message is called the primary search response. Each receiver which composes the primary search response sends the primary search response to the Host.

The Host aggregates the primary search responses and makes a decision to estimate the location of the transmitter, or to not do so. This decision is based on the content of the message in the target transmission, the identity of the transmitter, the availability of resources required to estimate the location of the transmitter, and other opportunities or requirements for the use of said resources.

If the Host decides to estimate the location of the transmitter and the Host determines that the primary search responses are sufficient for this purpose, the Host proceeds to estimate the location of the transmitter using the primary search responses. The Host is looking for three good responses from three different sites. In practice, the secondary search may always be required.

If the Host decides to estimate the location of the transmitter and the Host determines that the primary search responses may not be sufficient for this purpose, the Host proceeds to send message called the secondary search order to each receiver in the secondary search set (3104). The secondary search order sent to a receiver contains some or all of the following information:

- the approximate time or a range of times (a window) at which the receiver shall attempt to detect the target transmission,
- the approximate frequency or a range of frequency offsets at which the receiver shall attempt to detect the target transmission,
- some or all of the signal and message content of the target transmission,
- the amount of processing gain or observation time which the receiver shall use to search for the target transmission,
- the expected direction of arrival of the target transmission, and
- the priority of this search.

Upon receiving the secondary search order, a receiver executes the search for the target transmission in accordance with the content of said order.

After execution of the specified secondary search, a receiver composes a message called the secondary search response, which is sent to the Host (3105). The secondary search response contains the following information:

- an indication of whether or not the receiver succeeded in detecting the target transmission (3106),
- the time of arrival of the detected target transmission, if applicable,
- the frequency offset of the detected target transmission, if applicable,
- the carrier phase of the detected transmission, if applicable,
- the strength of arrival of the detected target transmission, if applicable,
- the ratio of the energy of the detected target transmission to the noise and interference power in the received signal, if applicable, and
- the ratio of bit energy of the detected target transmission to the noise power in the received signal, if applicable.

The Host collects the primary and secondary search responses associated with the target transmission and uses them to estimate the location of the transmitter.

In the preferred embodiment of the invention, receivers in the secondary search set store a representation of their respective received signals in memory, to enable the receivers to search for a prior target transmission, as directed by a secondary search order. Said representation is stored in a circular buffer, such that at any instant in time, the received signal over a period of time extending from the present to T_B seconds prior is stored. T_B is known as the depth of signal storage. The preferred value of T_B is three seconds. T_B should be selected so as to be greater than the maximum expected delay between reception of the target transmission by a receiver in the secondary search set, and reception of a secondary search order for that target transmission by said receiver. If the target transmissions are known to be slotted (only transmitted at certain times), then the signal storage can be implemented only for the times over which reception of the target transmission is expected.

Note that a receiver may be a member of both the primary and secondary search sets. In general, the secondary search set will include any receivers with reasonable probability of detecting the target transmission in a secondary search.

The preferred method of determining the secondary search sets is to assign a secondary search set to each receiver, and when said receiver reports a primary detection, the members of its secondary search set are included in the secondary search set for the target transmission. A receiver's secondary search set is initially set to the 5 receivers closest to said receiver. Over time, additional receivers are temporarily added to the secondary search set when doing so utilizes idle system resources, and if they demonstrate reasonable probability of detecting the target transmission, they are added on a permanent basis. A member of the secondary search set which demonstrates less than reasonable probability of such detection is removed from the secondary search set.

In this context, the preferred interpretation of "reasonable probability of detection" is a probability of 0.01 (1 percent) or more.

A receiver 3002 performs some or all of the following measurements on received transmissions:

- SNR,
- SOA,
- POA,
- FOA,
- TOA, and
- message decoding.

SNR, signal to noise ratio, is the ratio of the detected signal energy to the power of the non-signal components in the received signal. This serves as a measure of the confidence in the detection.

SOA, strength of arrival, is the strength of the received signal. The preferred units for this measurement are dBm.

POA, phase of arrival, is the carrier phase of arrival of the detected signal transmission.

FOA, frequency of arrival, is the frequency offset of the detected signal transmission.

TOA, time of arrival, is the time of arrival of the detected signal transmission.

In the MLR system, receivers are numbered $1,2,3,...,N_R$ where N_R is the number of receivers. When measurements of a particular transmission are reported and collected by the MLR Host, they are designated as follows. For a particular transmission, some receivers may not report detection nor measurements, and hence some of the following quantities may be undefined.

- SOA(R) is the SOA measured and reported by receiver R, $1 \le R \le N_R$.
- FOA(R) is the FOA measured and reported by receiver R, $1 \le R \le N_R$.
- TOA(R) is the TOA measured by receiver R, $1 \le R \le N_R$.
- POA(R) is the POA measured by receiver R, $1 \le R \le N_R$.
- SNR(R) is the SNR measured and reported by receiver R, $1 \le R \le N_R$.

The backhaul communications network 3003 provides a bi-directional communications link between the MLR Host 3004 and all receivers 3002. This network will carry primary notifications, orders to execute secondary searches, primary and secondary search responses, and other messages for configuration, control, and operation.

The MLR host 3004 will generate and receive messages related to primary and secondary detections, and will configure and monitor the receivers 3002, as described in previous sections. This section will focus on the two main tasks of the MLR Host 3004, which are (1) to use measurements reported by receivers to train the MLR distribution, and (2) to use the MLR distribution and measurements reported by receivers to estimate the location of a transmitter.

When the MLR Host 3004 receives measurements from one or more receivers, the MLR Host 3004 assigns a detection value $\beta(R)$ to each receiver. If receiver R

detected the target transmission, then the Host 3004 assigns $\beta(R)=1$. If receiver R did not detect the target transmission, then the Host 3004 assigns $\beta(R)=0$.

The preferred means of determining whether or not detection was successful is by comparing the observed SNR with a fixed threshold. Hence, if $SNR(R) \geq SNR_{min}$ then receiver R is deemed to have detected the target transmission and $\beta(R)=1$. If $SNR(R) < SNR_{min}$ then receiver R is deemed to have not detected the target transmission and $\beta(R)=0$.

The Host 3004 also attempts to determine the position co-ordinates of the transmitter by means other than MLR. If this position is thus obtained, then x represents the x co-ordinate, and y the y co-ordinate of the transmitter. The preferred co-ordinate system measures the distance in metres East (x) and North (y) from an origin point.

When the Host 3004 computes an SDOA as the difference of two SOAs, the SDOA may be represented by the variable "s".

The purpose of quantization is to transform a range of closely associated values to a single value which adequately represents said range of values. Said single value is used as a discretely-valued index along a dimension of the MLR distribution, D. This process may be referred to as "binning".

The quantization function $Q(a;b,c,d)$ is used to transform an observed parameter (x, y, or s) into a quantized index.

$$Q(A;B,C,D)=\begin{cases} 0 & \text{if } A \leq B, \\ \text{round}\left(\dfrac{A-B}{D}\right) & \text{if } B < A < C, \\ \text{round}\left(\dfrac{C-B}{D}\right) & \text{if } A \geq C. \end{cases}$$

An x-position is quantized as follows:

$$Q(x;x_{min},x_{max},\Delta x)=\begin{cases}0 & \text{if } x \le x_{min},\\ \mathrm{round}\left(\dfrac{x-x_{min}}{\Delta x}\right) & \text{if } x_{min}<x<x_{max},\\ \mathrm{round}\left(\dfrac{x_{max}-x_{min}}{\Delta x}\right) & \text{if } x \ge x_{max}.\end{cases}$$

A y-position is quantized as follows:

$$Q(y;y_{min},y_{max},\Delta y)=\begin{cases}0 & \text{if } y \le y_{min},\\ \mathrm{round}\left(\dfrac{y-y_{min}}{\Delta y}\right) & \text{if } y_{min}<y<y_{max},\\ \mathrm{round}\left(\dfrac{y_{max}-y_{min}}{\Delta y}\right) & \text{if } y \ge y_{max}.\end{cases}$$

A SDOA (s) is quantized as follows:

$$Q(s;s_{min},s_{max},\Delta s)=\begin{cases}0 & \text{if } s \le s_{min},\\ \mathrm{round}\left(\dfrac{s-s_{min}}{\Delta s}\right) & \text{if } s_{min}<s<s_{max},\\ \mathrm{round}\left(\dfrac{s_{max}-s_{min}}{\Delta s}\right) & \text{if } s \ge s_{max}.\end{cases}$$

The rounding function $\mathrm{round}(\cdot)$ returns the closest integer to its argument, or the next larger integer if the argument is equally close to two integers.

An "un-quantizing" function U(I;B,C,D) is defined in order to transform a quantized index I to a value which is close to observed values which have a quantized value of I.

$U(I;B,D) = I \cdot AD + B$

Note that with respect to the first argument of both functions, U(I;B,D) inverts the function Q(A;B,C,D) to within a tolerance of D, provided that A is within the range $B \le A \le C$.

An x-position index I_x is unquantized by $U(I_x;x_{min},\Delta x) = I_x \Delta x + x_{min}$.

A y-position index i_Y is unquantized by $U(I_y; y_{min}, \Delta y) = I_y \Delta y + y_{min}$.

The MLR Host 3004 maintains a data structure D, called the MLR distribution. D is a 5-dimensional numeric array.

An element of D is denoted $D(R_1, R_2, I_X, I_Y, I_S)$, where

R_1 is a number which identifies a receiver, $1 \le R_1 \le N_R$,

R_2 is a number which identifies another receiver, $1 \le R_2 \le N_R$,

I_x is a quantized x-position, $0 \le I_x < \mathrm{round}\left(\frac{x_{max} - x_{min}}{\Delta x}\right)$,

I_y is a quantized y-position, $0 \le I_y < \mathrm{round}\left(\frac{y_{max} - y_{min}}{\Delta y}\right)$, and

I_s is a quantized SDOA observation, $0 \le I_s < \mathrm{round}\left(\frac{s_{max} - s_{min}}{\Delta s}\right)$.

Thus, the dimensions of D are $N_R \times N_R \times \mathrm{round}\left(\frac{x_{max} - x_{min}}{\Delta x}\right) \times \mathrm{round}\left(\frac{y_{max} - y_{min}}{\Delta y}\right) \times \mathrm{round}\left(\frac{s_{max} - s_{min}}{\Delta s}\right)$.

This section defines procedures executed by the MLR Host 3004.

Procedure 1: Overall Operation of MLR

step 1: Initialize the MLR data structure D by setting all of its elements to zero.

step 2: Wait until a single transmission is detected by one or more receivers, then proceed with step 3.

step 3: Attempt to determine or obtain the position of the transmitter by means other than MLR. If the position is thusly obtained, then execute Procedure 2, otherwise execute Procedure 3.

step 4: Return to step 2.

Procedure 1 defines the overall operation of MLR. The secondary search method is included in step 2. When the transmitter position is provided along with a set of SOA observations, the Host 3004 can train the MLR distribution using Procedure 2. If a set of SOA observations is provided without the transmitter position, the Host 3004 can estimate the transmitter position using Procedure 3. In general, it is beneficial to train the MLR distribution as much as possible.

Procedure 2: MLR Training

step 1: Let x, y be the known x and y co-ordinates, respectively, of the transmitter.

step 2: Compute $I_X = Q(x; x_{min}, x_{max}, \Delta x)$.

step 3: Compute $I_Y = Q(y; y_{min}, y_{max}, \Delta y)$.

step 4: For $R_1 = 1, 2, 3, \ldots, N_R - 1$ execute step 5.

step 5: For $R_2 = R_1 + 1, R_1 + 2, \ldots, N_R$ execute steps 6 to 8.

step 6: If $\beta(R_1) = 1$ and $\beta(R_2) = 1$ then compute $I_S = Q(SOA(R_1) - SOA(R_2); s_{min}, s_{max}, \Delta s)$ and increase $D(R_1, R_2, I_X, I_Y, I_s)$ by 1.

step 7: If $\beta(R_1) = 1$ and $\beta(R_2) = 0$ and $D(R_1, R_2, i, j, k)$ is nonzero for any values of i, j, and k then let $I_S = Q(s_{max}; s_{min}, s_{max}, \Delta s)$ and increase $D(R_1, R_2, I_X, I_Y, I_s)$ by 1.

step 8: If $\beta(R_1) = 0$ and $\beta(R_2) = 1$ and $D(R_1, R_2, i, j, k)$ is nonzero for any values of i, j, and k then let $I_S = Q(s_{min}; s_{min}, s_{max}, \Delta s)$ and increase $D(R_1, R_2, I_X, I_Y, I_s)$ by 1.

Note that for each pass through the inner loop (steps 6-8), no change is made to D if $\beta(R_1) = 0$ and $\beta(R_2) = 0$.

Steps 7 and 8 incorporate a rule by which training for a pair of receivers R1, R2 is suppressed if those two receivers are unlikely to contribute to estimation. It is deemed unlikely that a pair of receivers will contribute to estimation if they have no coverage overlap, i.e. there are no previously recorded cases in which they have both detected the transmission. This rule is especially effective in limiting the size of the sparse matrix representation of the MLR distribution, D.

Procedure 3: MLR Estimation

step 1: Let S_P be the set of 2 dimensional likelihood distributions for position estimation of this transmission. Initialize S_P to be the empty set.

step 2: Compute $N_X = Q(x_{max}; x_{min}, x_{max}, \Delta x) + 1$, the number of x bins.

step 3: Compute $N_Y = Q(y_{max}; y_{min}, y_{max}, \Delta y) + 1$, the number of y bins.

step 4: For $R_1 = 1,2,3,\ldots,N_R - 1$ execute step 5.

step 5: For $R_2 = R_1 + 1, R_1 + 2, \ldots, N_R$ execute steps 6 through 10 inclusive.

step 6: If $\beta(R_1) = 1$ and $\beta(R_2) = 1$ then compute $I_S = Q(SOA(R_1) - SOA(R_2); s_{min}, s_{max}, \Delta s)$

step 7: If $\beta(R_1) = 1$ and $\beta(R_2) = 0$ then let $I_S = Q(s_{max}; s_{min}, s_{max}, \Delta s)$.

step 8: If $\beta(R_1) = 0$ and $\beta(R_2) = 1$ then let $I_S = Q(s_{min}; s_{min}, s_{max}, \Delta s)$.

step 9: If $\beta(R_1) = 1$ or $\beta(R_2) = 1$ then create the two-dimensional likelihood distribution P with elements $P(I_X, I_Y) = D(R_1, R_2, I_X, I_Y, I_S)$ for $0 \le I_X < N_X$, $0 \le I_Y < N_Y$.

step 10: If $\beta(R_1)=1$ or $\beta(R_2)=1$ then add (include, not sum) P in the set S_P.

step 11: Denote the members of set S_P, in any order, as $P_1, P_2, P_3, \ldots, P_{N_P}$ where N_P is the number of two-dimensional likelihood distributions in S_P.

step 12: For $0 \le l_X < N_X$, $0 \le l_Y < N_Y$ compute

$$P_{combined}(l_X, l_Y) = \prod_{n=1}^{N_P} P_n(l_X, l_y) + p_0 = (P_1(l_X, l_y) + p_0) \cdot (P_2(l_X, l_y) + p_0) \cdots (P_{N_P}(l_X, l_y) + p_0)$$

step 13: Compute $\hat{x} = \dfrac{\sum_{l_X=0}^{N_X-1} \sum_{l_Y=0}^{N_Y-1} U(l_X, x_{min}, \Delta x) \cdot [P_{combined}(l_X, l_Y)]^{\alpha}}{\sum_{l_X=0}^{N_X-1} \sum_{l_Y=0}^{N_Y-1} [P_{combined}(l_X, l_Y)]^{\alpha}}$.

step 14: Compute $\hat{y} = \dfrac{\sum_{l_X=0}^{N_X-1} \sum_{l_Y=0}^{N_Y-1} U(l_Y, y_{min}, \Delta y) \cdot [P_{combined}(l_X, l_Y)]^{\alpha}}{\sum_{l_X=0}^{N_X-1} \sum_{l_Y=0}^{N_Y-1} [P_{combined}(l_X, l_Y)]^{\alpha}}$.

For a given pair of receivers, steps 6 - 8 attempt to select a spatial likelihood distribution for the transmitter location, based on the observed or assumed SDOA for that receiver pair.

Step 12 combines all selected spatial likelihood distributions into a single likelihood distribution. The constant p_0 is added to all samples to prevent a bin value of zero from completely nullifying other potentially high bin values for the same spatial region.

Steps 13 and 14 compute a moment of variable order (α) of the combined spatial likelihood distribution. If $\alpha = 1$, the first-order moment, or mean, is computed. The preferred value of $\alpha = 1.5$ will yield a result which is similar to the mean, but which places increased emphasis on higher likelihood values. The MLR estimated location of the source of the transmission is given by the co-ordinates $(\hat{x}, \hat{y})$.

Adding a new receiver to an existing MLR network can be accomplished by increasing N_R by one to reflect the new number of receivers. Also, the first two dimensions of the MLR distribution D by one, and the new elements created thereby should be initialized to zero.

Deleting a receiver is accomplished by removing the elements of D corresponding to the receiver to be deleted, and re-ordering the remaining elements so that the first two dimensions have indices from 1 to the number of receivers after deletion. N_R should be updated accordingly.

If it is known or can be determined that a receiver is currently non-operational, then it should be temporarily excluded from training and estimation so that failure to detect by the non-operational receiver under circumstances in which said receiver would normally have detected does not distort training or estimation.

If it is known or can be determined that the gain of receiver R has changed, such that all subsequent SOA measurements will be offset by a fixed amount compared to previous measurements, then the MLR distribution D should be updated by shifting all elements corresponding to receiver R to new indicies, offset along the SDOA dimension by an amount and direction corresponding to the change in gain, such that the MLR distribution may be expected to reflect the new receiver characteristics.

If it is known or can be determined that receiver R has changed in a manner which is not easily compensated for by an adjustment to the MLR distribution, then receiver R should be deleted and added to the MLR distribution in order to clear out previous training data for R, which may no longer be valid. Examples of such changes include adjustment of receiver antenna orientation or position.

In order to allow the MLR distribution to adapt to changing propagation conditions, it is desirable to implement some means by which more recent training data is more strongly weighted than other training data. The preferred means of accomplishing this is to replace each element in the MLR distribution with a fraction λ of its previous value:

$D(R_1,R_2,l_X,l_Y,l_S) \leftarrow \lambda \cdot D(R_1,R_2,l_X,l_Y,l_S)$, for all elements of D.

In order to achieve a desirable balance between accumulation and diminution of training data, the preferred rule for applying the forgetting factor is to do so when the average value of nonzero elements of D exceeds a threshold D_0. D_0 is called the Targeted Mean Distribution Value, since with continual training, the mean value of nonzero elements of D will be close to D_0. When this value exceeds D_0, it will be decreased by application of the forgetting factor. When this value is less than D_0, it will increase due to training.

Table 1 lists the configuration parameters for MLR, and their preferred values under anticipated or typical conditions.

parameter	preferred value	description
s_{min}	-30 dB	lowest SDOA bin
s_{max}	+30 dB	highest SDOA bin
Δs	1 dB	SDOA bin separation
x_{min}	-20,000 m	lowest x co-ordinate
y_{min}	-20,000 m	lowest y co-ordinate
x_{max}	20,000 m	highest x co-ordinate
y_{max}	20,000 m	highest y co-ordinate
Δx	50 m	x dimension bin size
Δy	50 m	y dimension bin size
SNR_{min}	12 dB	minimum SNR for successful detection

origin	center of the RML network area	origin point from which the x co-ordinates are measured East, and y co-ordinates are measured North
p_0	2	offset for MLR combining
λ	0.9	MLR distribution forgetting factor
D_0	20	Targeted mean distribution value

Table 1: Preferred Values for MLR Parameters

s_{max} should be set to the difference, in dB, between the largest SOA observed or expected and the smallest SOA observed or expected which can be detected with reasonable confidence. This is a positive number.

s_{min} should be set the negative of s_{max}.

Δs should be set to the precision with which SOA can be measured.

x_{min} should be set to the lowest x co-ordinate for which the ML-R system will be capable of estimating positions.

y_{min} should be set to the lowest x co-ordinate for which the ML-R system will be capable of estimating positions.

x_{max} should be set to the highest y co-ordinate for which the ML-R system will be capable of estimating positions.

y_{max} should be set to the highest y co-ordinate for which the ML-R system will be capable of estimating positions.

An origin point is selected for the MLR network. This selection is fairly arbitrary, it merely serves as a reference for x and y position measurements. A preferred location of the origin is the origin of a UTM co-ordinate system. An

alternative preferred location for the origin is the center of the region over which MLR is to be implemented.

For example, suppose that MLR is to be implemented over the region of the city of Calgary, Alberta, Canada, and the origin (the point with co-ordinates x=0, y=0) is selected to be a landmark in the center of the city. The MLR network area is chosen to encompass a square with sides 20 km from the origin. The spatial units selected are metres, so xmin=ymin=20000 m while xmax=ymax=20000m.

Δx and Δy should be set to the smallest distance along their respective dimensions over which the average SDOA is expected to vary by Δs. Δx and Δy should not be smaller than the precision of (x,y) positions used for training.

Maximum-Likelihood Region estimation as described in the preceding sections, makes use of measurements collected by multiple receivers of a transmission from a single transmitter in order to estimate the location the transmitter. This may be more specifically identified as Reverse-Link MLR. The underlying concepts can be applied to a reciprocal situation in which a single receiver measures the SOAs of multiple signals, transmitted from multiple transmitters. This embodiment is particularly applicable to cellular standards in which the mobile units measure and report signal strengths of pilot or beacon signals from multiple cell sties or sectors. Such is the case with IS-136 TDMA and GSM, in which the mobile searches for control signals from potential handoff candidates in idle timeslots.

Forward-Link MLR should include a correction factor for variations in the transmit power of signals for which SOA measurements are made. This affords an opportunity to utilize absolute SOA, rather than SDOA measurements.

In Forward Link MLR, the role of the transmitter (from Reverse Link MLR) is replaced by a single receiver, also called the mobile unit, and the SOA reported by each receiver (in Reverse Link MLR) is replaced by the SOA from one of the many transmitters, potentially measured and reported by the single receiver.

Another alternative embodiment of MLR incorporates both forward link and reverse link measurements. The object of such a system is to determine the location of a mobile unit which both transmits and receives. This can be done by

implementing Reverse Link MLR, and treating each forward link SOA (measured at the mobile unit) as an additional receiver represented in the MLR likelihood distribution.

MLR can be readily extended to additional dimensions - spatial, temporal, or otherwise, beyond the two (x,y) described previously

TDOA measurements can be used in place of or in addition to SDOA measurements, in MLR.

In the preferred embodiment of this invention, the observations SOA(R) are used, while the other observations, TOA(R), FOA(R), SNR(R), and POA(R) are not used. However, they may be incorporated in alternative embodiments after the fashion of SOA(R) as described in the preferred embodiment.

In an embodiment in which the transmit power of the transmitter is known or can be determined, the use of SOA measurements directly rather than SDOA measurements may enhance the performance of the system. The system may be further enhanced by using a combination of both SOA and SDOA.

In yet another embodiment of the invention, diverse signal measurements associated with both forward and reverse link signals can be incorporated training and estimation with a MLR distribution.

The preferred embodiment for the invention incorporates a cellular communications network, consisting of multiple base stations and mobile transceivers. However, the invention can be generalized to one or more transmitting devices and a collection of receivers that are capable of receiving signals from the transmitting devices. One alternative embodiment of the invention would be a collection of transmitting devices each capable of transmitting a signal with specified characteristics on demand or at regular intervals, and a collection of receivers, each located near a cellular base station, each receiver being capable of receiving transmissions from said transmitters.

In the preferred embodiment of the invention, D is implemented as a sparse array (D_S) in order to achieve efficient storage. D_S is organized as a two-

dimensional array having 6 columns, and a number of rows equal to the number of nonzero elements in D. The six elements of each row if D_S represent the 5 indices and the (nonzero) value of one element of D. Any element of D not represented by a row of D_S has a value of zero. This storage method is efficient for storing a 5-dimensional array for which most of the elements have a value of zero, as is the expected case for the MLR Distribution. Nonetheless, the implementation of the this invention is fairly independent of whether D is stored as a full 5-dimensional array or as a sparse array.

The quantization of observations is a rule by which an unquantized observation is associated with a quantized observation. In the preferred embodiment, a quantization scheme consisting of uniform intervals defined by a few configuration parameters is used. Alternative embodiments may incorporate other means of quantization, including non-uniform levels and levels which are adapted to the nature of the observed data.

In yet another embodiment of the invention, the transmitter emits transmissions at semi-regular or predictable intervals. Receivers in the secondary search set are not required to store or buffer the received signal. A primary detection report triggers a secondary search of a subsequent transmission, the time of which is either a fixed offset from the first transmission, or can be predicted from the first transmission.

Instructions for a computer to carry out each of the algorithms described here, including the secondary search, grouped coherent detection, and the procedures A1-A10 for FML-AOA, and procedures 1-3 for MLR, as well as the procedures for precise positioning of a transmitter, may be stored on computer readable media, loaded into a general purpose computer or hardwired into a special purpose digital processor.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A method of locating a transmitter with respect to a receiver, where the transmitter is in communication with the receiver, the method comprising the steps of:

a) storing, in a database, a first set of likelihood functions, each likelihood function comprising a series of values representing the probability that a measure of location corresponds to a value of a first signal parameter, the first signal parameter being a function of a measured characteristic of signals received at the receiver;

b) receiving signals at the receiver from the transmitter;

c) estimating a value of the first signal parameter from the received signals; and

d) locating the transmitter with respect to the receiver by determining a measure of location which, by reference to the likelihood functions for the first signal parameter, corresponds to the estimated value of the first signal parameter.

2. The method of claim 1 further including the step of:

storing, in a database, a second set of likelihood functions, each of the second set of likelihood functions comprising a series of values representing the probability that a measure of location corresponds to a value of a second signal parameter, the second signal parameter being a function of a measured characteristic of signals received at the receiver;

estimating a value of the second signal parameter from the received signals; and

resolving ambiguities in the location of the mobile transmitter by reference to the likelihood function corresponding to the estimated value of the second signal parameter.

3. The method of claim 2 in which resolving ambiguities in the location of the transmitter with respect to the receiver comprises combining the likelihood function corresponding to the estimated value of the first signal parameter and the likelihood function corresponding to the estimated value of the second signal parameter.

4. The method of claim 3 in which combining the likelihood functions comprises multiplying the likelihood functions.

5. The method of claim 1 in which ambiguities in the location of the transmitter with respect to the receiver are resolved by reference to measures of location based on signals received at additional receivers.

6. The method of claim 5 in which the measure of location is the angle of arrival of the received signals.

7. The method of claim 5 in which the first signal parameter is a function of the phase of the received signals.

8. The method of claim 5 in which the first signal parameter is the difference of the phase of received signals.

9. The method of claim 5 in which the first signal parameter is a function of the strength of the received signals.

10. The method of claim 5 in which the first signal parameter is the ratio of the strength of received signals.

11. The method of claim 2 in which:

the measure of location is the angle of arrival of the received signals;

the first signal parameter is a function of the phase of the received signals: and

the second signal parameter is a function of the strength of the received signals.

12. The method of claim 1 in which the likelihood functions are constructed by an adaptive procedure.

13. The method of claim 12 in which:

the likelihood functions are constructed by defining distinct bins, each bin being bound by corresponding upper and lower bounds of the measure of location and the first signal parameter; and

a bin is incremented in value when, for a transmitter with a known measure of location with respect to the receiver and a measured first signal parameter, the known measure of location and measured first signal parameter fall within the upper and lower bounds of the bin.

14. The method of claim 1 in which the likelihood functions are trained using a different signal parameter from the first signal parameter.

15. The method of claim 14 in which the likelihood functions are stored at monitoring sites and the likelihood functions are trained when the monitoring sites are otherwise idle.

16. The method of claim 1 in which the likelihood functions are initialized by estimates.

17. The method of claim 1 further comprising repeating steps b, c and d of claim 1 several times to obtain several estimates of the measure of location and obtaining a value for the measure of location from the several estimates.

18. The method of claim 17 in which obtaining a value for the measure of location comprises obtaining the mean of the several estimates.

19. The method of claim 1 in which the receiver is mobile, the transmitter has known location and signals are received at plural antennas at the receiver.

20. The method of claim 1 in which the transmitter is mobile, the receiver has known location and the signals are received at plural antennas.

21. The method of claim 1 in which the antennas are located at plural monitoring sites, and the receiver is at one of the monitoring sites.

22. The method of claim 1 in which the transmitter is a mobile transceiver.

23. The method of claim 1 in which the transmitter transmits in response to a page from a monitoring site.

24. The method of claim 1 in which, after the receiver has received a signal from the transmitter, at least another receiver is instructed to detect transmissions from the transmitter.

25. The method of claim 1 in which signals from the transmitter are received at an initial set of receivers, and upon detection at the initial set of receivers, a second set of receivers is instructed to detect the transmission.

26. A method of locating a mobile transmitter in relation to a monitoring site having at least first and second antennas, the method comprising the steps of:

a) storing, in a database, a first set of likelihood functions, each likelihood function comprising a series of values representing the probability that a measure of

location corresponds to a value of a first signal parameter, the first signal parameter being a function of signals received at the first and second antennas;

b) receiving received signals at the first and second antennas;

c) estimating an estimated value of the first signal parameter from the received signals; and

d) locating the mobile transmitter by determining a measure of location which, by reference to the likelihood functions for the first signal parameter, corresponds to the estimated value of the first signal parameter.

27. The method of claim 26 further including the step of:

storing, in a database, a second set of likelihood functions, each of the second set of likelihood functions comprising a series of values representing the probability that a measure of location corresponds to a value of a second signal parameter, the second signal parameter being a function of signals received at at least one of the first and second antennas;

estimating an estimated value of a second signal parameter from the received signals; and

resolving ambiguities in the location of the mobile transmitter by reference to the likelihood function corresponding to the estimated value of the second signal parameter.

28. The method of claim 27 in which resolving ambiguities in the location of the mobile transmitter comprises combining the likelihood function corresponding to the estimated value of the first signal parameter and the likelihood function corresponding to the estimated value of the second signal parameter.

29. The method of claim 28 in which combining the likelihood functions comprises multiplying the likelihood functions.

30. The method of claim 29 in which resolving ambiguities in the location of the mobile transmitter is resolved by reference to measures of location based on signals received at additional monitoring sites.

31. The method of claim 26 in which the measure of location is the angle of arrival of the received signals.

32. The method of claim 26 in which the first signal parameter is a function of the phase of the received signals.

33. The method of claim 26 in which the first signal parameter is the difference of the phase of the received signals at the first and second antennas.

34. The method of claim 26 in which the first signal parameter is a function of the strength of the received signals.

35. The method of claim 26 in which the first signal parameter is the ratio of the strength of the received signals at the first and second antennas.

36. The method of claim 27 in which:

the measure of location is the angle of arrival of the received signals;

the first signal parameter is a function of the phase of the received signals; and

the second signal parameter is a function of the strength of the received signals.

37. The method of claim 26 in which the likelihood functions are constructed by an adaptive procedure.

38. The method of claim 37 in which:

the likelihood functions are constructed by defining distinct bins, each bin being bound by corresponding upper and lower bounds of the measure of location and the first signal parameter; and

a bin is incremented when, for a mobile transmitter with a known measure of location and a measured first signal parameter, the known measure of location and measured first signal parameter fall within the upper and lower bounds of the bin.

39. The method of claim 26 in which the likelihood functions are trained using a different signal parameter from the first signal parameter.

40. The method of claim 26 in which the likelihood functions are trained when the monitoring site is otherwise idle.

41. The method of claim 26 in which the likelihood functions are initialized by estimates.

42. The method of claim 26 further comprising repeating steps b, c and d of claim 26 several times to obtain several estimates of the measure of location and obtaining a value for the measure of location from the several estimates.

43. The method of claim 42 in which obtaining a value for the measure of location comprises obtaining the mean of the several estimates.

44. A method of locating a mobile transmitter, the method comprising the steps of:

detecting a transmission from a mobile transmitter at several receivers;

grouped-coherent detecting the transmissions to yield a derived signal; and

processing the derived signal to find the location of the mobile transmitter.

45. The method of claim 44 in which grouped-coherent detecting the transmissions comprises:

selecting trial values of the time of arrival of the transmission at a monitoring site over a time interval;

correlating the transmission with the trial values over plural subintervals of the time interval to yield subinterval correlations;

coherently combining the subinterval correlations at trial frequencies to yield a set of values of a function $z(\tau, F)$ where τ is a time estimate and F is a frequency estimate; and

selecting one of the time estimates and one of the frequency estimates as the time and frequency of arrival of the transmission.

46. The method of claim 45 in which the selected one of the time estimates is the time estimate yielding a maximum value of $z(\tau, F)$ and the selected one of the frequency estimates is the frequency estimate yielding a maximum value of $z(\tau, F)$.

47. The method of claim 45 in which coherently combining the subinterval correlations comprises computing a Fast Fourier Transform over the subinterval correlations.

48. The method of claim 45 further comprising refining the time of arrival estimate by computing subinterval correlations with a finer spacing of trial values.

49. The method of claim 44 further comprising finding the rising edge of the transmitted signal as it is received by the receivers.

50. The method of claim 45 in which the phase of arrival of the transmitted signal is detected by coherently combining the subinterval correlations without magnitude squaring.

51. The method of claim 45 in which the strength of arrival of the transmitted signal at the receivers is defined as a function of the maximum value of $z(\tau, F)$.

52. A method for estimating the angle at which a group of two or more transmitters of wireless signals lies with respect to a receiver of wireless signals, in which the difference in strengths of the two received signals is used to compute or select the most likely angle.

53. The method of claim 52 in which a set of numbers representing the likelihood for various angles is selected, from a number of such sets, which has an associated difference in signal strengths which is closest to the observed difference of signal strengths.

54. The method of claim 53 in which failure to detect one of the two signals is interpreted as a fixed difference in signal strength.

55. The method of claim 54 in which multiple pairings of transmitting antennas are used to select multiple sets of numbers representing likelihood of angles of arrival, and the selected sets are combined into one set from which the Angle of arrival is estimated.

56. A method for generating a set of numbers representing the two-dimensional likelihood distribution with respect to differencc in strength of arrival and angle of arrival, for a receiver which receives signals from multiple transmitters, in which the observations of pairings of difference in strength of arrival and angle of arrival are madc, and for each observation, the element within thc distribution most closely associated with the observed difference in strength of arrival and angle of arrival is increased.

57. The method of claim 56 in which said element is increased by a fixed quantity.

58 The method of claim 57 in which said element is increased by a quantity which is the result of a monotonic function of the confidence in the observed angle of arrival and difference in strength of arrival.

59. The method of claim 53 in which the sets of numbers are initialized according to typical antenna gain patterns based on the azimuths and possibly including the sector widths of the transmitting antennas.

60. The method of claim 53 in which the two-dimensional distribution is initialized with piecewise linear segments having endpoints at the azimuths of the transmitting antennas.

61. The method of claim 56 in which the angle of arrival is computed from the known coordinates of the transmitter station, and the coordinates of the receiver as determined by the Global Positioning System.

62. The method of claim 56 in which the angle of arrival is computed from the known coordinates of the transmitter station, and the coordinates of the receiver as determined by time difference of arrival of signals transmitted from a transmitter situated with said receiver, and said signals are received at various other locations, possibly including that of the first group of transmitters.

63. The method of claim 53 in which said set of numbers is selected from a likelihood distribution generated by:

making observations of pairs of difference in strength of arrival and angle of arrival, and for each observation, an element within a probability distribution most closely associated with the observed difference in strength of arrival and angle of arrival is increased.

64. The method of claim 63 further comprising smoothing the probability distribution.

65. A method for estimating the angle, relative to some reference angle, between the location of an antenna receiving wireless signals and a group of two antennas transmitting wireless signals, in which the difference in phases of the two received signals is used to compute or select the most likely angle.

66. The method of claim 65 in which a set of numbers representing the likelihood for various angles is selected, from a number of such sets, which has an associated difference in signal phases which is closest to the observed difference of signal phases.

67. The method of claim 66 in which multiple pairings of transmitting antennas are used to select multiple sets of numbers representing likelihood of angles of arrival, and the selected sets are combined, in a suitable manner, into one set from which the Angle of arrival is estimated.

68. The methods of any one of claims 53 and 66 in which multiple pairings of transmitting antennas are used to select multiple sets of numbers representing likelihood of angles of arrival, some sets with respect to difference in observed signal strength, some sets with respect to difference in observed phases, and the selected sets are combined, in a suitable manner, into one set from which the angle of arrival is estimated.

69. A method for generating a set of numbers representing the two-dimensional likelihood distribution with respect to difference in phase of arrival and angle of arrival, for a receiver which receives signals from multiple transmitters, in which the observations of pairings of difference in phase of arrival and angle of arrival are made, and for each observation, the element within the distribution most closely

associated with the observed difference in phase of arrival and angle of arrival is increased.

70. The method of 69 in which said element is increased by a fixed quantity.

71. The method of claim 69 in which said element is increased by a quantity which is the result of a monotonic function of the confidence in the observed angle of arrival and the difference in strength of arrival.

72. The method of claim 69 in which the angle of arrival is computed from the known coordinates of the transmitter station, and the coordinates of the receiver as determined by the Global Positioning System.

73. The method of claim claim 69 in which the angle of arrival is computed from the known coordinates of the transmitter station, and the coordinates of the receiver as determined by the time difference of arrival of signals transmitted from a transmitter situated with said receiver, and said signals are received at various other locations, possibly including that of the first group of transmitters.

74. The method of claim 66 in which said set of number is selected from the likelihood distribution of claim 69.

75. The method of claim 52 applied to transmitting antennas having different polarizations.

76. The method of claim 56 applied to training using forward-link trilateration.

77. A method for estimating the position of a wireless transmitter in which the difference in strengths of arrival of the signal transmitted by said transmitter at one or more pairs of receivers is used to select the a position.

78. The method of claim 77 in which a set of numbers P(ix,iy) representing the likelihood of various positions is selected from among a number of such sets, and the means of selection is to choose the set which has an associated SDOA closest to the observed SDOA.

79. The method of claim 78 in which failure to detect at one of a pair of receivers is optionally interpreted as a fixed difference in signal strength.

80. The method of claim 79 in which all possible pairings of receivers for which at least one receiver detected the transmission are used to select a set of numbers P(ix,iy), and the sets of numbers are combined in a suitable manner into one set from which the position of the wireless transmitter is estimated.

81. The method of claim 80 in which the sets of numbers P1(ix,iy), P2(ix,iy),...(etc.) are combined by adding a fixed number p_0 to each number of each set, and the product is taken all sums having the same indicies (ix,iy) in order to yield a single set of numbers $P_{combined}(i_x, i_y)$.

82. The method of claim 81 in which the (x,y) position estimate is first-order moment of the single resultant set of numbers $P_{combined}(i_x, i_y)$, transformed by scaling and offseting into the co-ordinate system represented by the quantized co-ordinates (ix,iy)

83. A method for generating a set of numbers D(ir1,ir2,is,ix,iy) representing the likelihood of association of an observed SDOA (is) for the pair of receivers (ir1,ir2) with a known or likely transmitter position (ix,iy) in which the number D(ir1,ir2,is,ix,iy) is increased in response to an observation (ir1,ir2,is,ix,iy).

84. The method of claim 83 in which D(ir1,ir2,is,ix,iy) is increased by a fixed amount in response to an observation (ir1,ir2,is,ix,iy).

85. The method of claim 83 in which D(ir1,ir2,is,ix,iy) is increased by a quantity which is the result of a monotonic function of a measure of confidence, such as SNR, of the observation (ir1,ir2,is,ix,iy).

86. A method of locating a mobile transmitter, the method comprising the steps of:

detecting signals transmitted from the mobile transmitter and received at a first receiver;

upon detecting signals from the mobile transmitter at the first receiver, instructing at least a second receiver to search for and detect signals transmitted by the mobile transmitter; and

locating the mobile transmitter by processing signals received at the first and second receivers.

87. The method of claim 86 in which signals from the mobile transmitter are received at an initial set of receivers, and upon detection at the initial set of receivers, a second set of receivers is instructed to search for and detect the signals from the mobile transmitter.

88. The method of claim 86 in which the second receiver is instructed to search for the mobile transmitter using characteristics of the signal received at the first receiver.

89. A method of detecting a transmission from a mobile transmitter, the method comprising the steps of:

detecting a transmission from a mobile transmitter at several monitoring sites to produce a received signal having an observation period;

correlating the received signal with a sought signal over subintervals of the observation period to produce subcorrelation results;

filtering the subcorrelation results to remove signal components outside of a range of preselected frequency offsets to produce filtered subcorrelation results; and

noncoherently combining the filtered subcorrelation results to produce a time of arrival estimate.

90. Computer readable media comprising instructions for a computer to carry out a wireless location procedure selected from the group consisting of the MLR procedures A1-A10 and 1-3.

91. A host computer programmed to carry out a wireless location procedure selected from the group consisting of the MLR procedures A1-A10 and 1-3.

92. Apparatus programmed to carry out any of the methods of any one of the preceding claims.

93. Computer readable media containing instructions for a computer to carry out any of the methods of any one of the claims 1-89.

94. A method of locating a transmitter, the method comprising the steps of:

receiving at multiple sites a signal from the transmitter;

processing the signal to yield observations of a first signal parameter corresponding to the received signal at each of the sites; and

applying a wireless location algorithm to the observations to yield an estimate of the location of the transmitter, in which wireless location algorithm the observations are weighted according to reliability of the corresponding received signal.

95. The method of claim 1 in which the wireless location algorithm is an iterative minimizing algorithm.

96. The method of claim 2 in which the iterative minimizing algorithm minimizes the sum of the squares of residual adjustments to the observations that are required to produce a solution.

97. The method of claim 3 further comprising the step of:

finding the received signal strength for each of the received signals to yield a received signal strength corresponding to each observation; and

the observations are weighted according to the received signal strength of the corresponding received signal.

98. The method of claim 4 in which an observation is excluded from processing when the observation is a blunder.

99. The method of claim 5 in which a selected one of misclosures and standardized residuals is used to flag observations that may be a blunder.

100. The method of claim 4 further comprising the step of:

excluding observations from application of the iterative minimizing algorithm when inclusion of an observation increases the standard deviation of the estimate of the location of the transmitter more than the dilution of precision of the estimate of the location of the transmitter.

101. The method of claim 2 in which a selected one of Chaffee's method, location on the conic axis and both Chaffee's method and location on the conic axis are used to detect solution bifurcation.

102. The method of claim 2 in which a selected one of location on the conic axis, plane intersection and both location on the conic axis and plane intersection are used to provide an initial position for an iterative algorithm.

103. The method of claim 1 in which each observation is the time difference between arrivals of the received signal at pairs of sites.

104. The method of claim 2 in which the iterative minimizing algorithm begins with an initial position based on the known locations of the sites.

105. A method of locating a mobile transmitter, wherein the mobile transmitter consists of a transmitter without audio section, the method comprising the steps of:

receiving signals from the mobile transmitter that are transmitted on cellular frequencies; and

processing the signals to estimate the location of the mobile transmitter.

106. A method of locating a mobile transmitter, the method comprising the steps of:

receiving signals from the mobile transmitter at plural receiving locations and processing the received signals to obtain a set of observations of first signal parameters; and

identifying observations that are blunders;

removing blunders from the set of observations; and

estimating the location of the mobile transmitter from the set of observations from which blunders have been removed.

107. The method of claim 13 in which observations are removed when inclusion of an observation increases the standard deviation of the estimate of the location of the mobile transmitter more than the dilution of precision of the estimate of the location of the mobile transmitter.

108. A method of locating a mobile transceiver having a ringer, the method comprising the steps of:

turning the ringer off;

paging the mobile transceiver;

instructing the mobile transceiver to transmit a signal;

receiving the signal from the mobile transceiver at a monitoring site; and

processing the signal received at the monitoring site.

109. A method of locating a mobile transmitter making a 911 call to a PSAP, the method comprising the steps of:

receiving at a PSAP a 911 call made by a mobile transmitter; and

locating the mobile transmitter while the PSAP is in unanswered conversation mode.

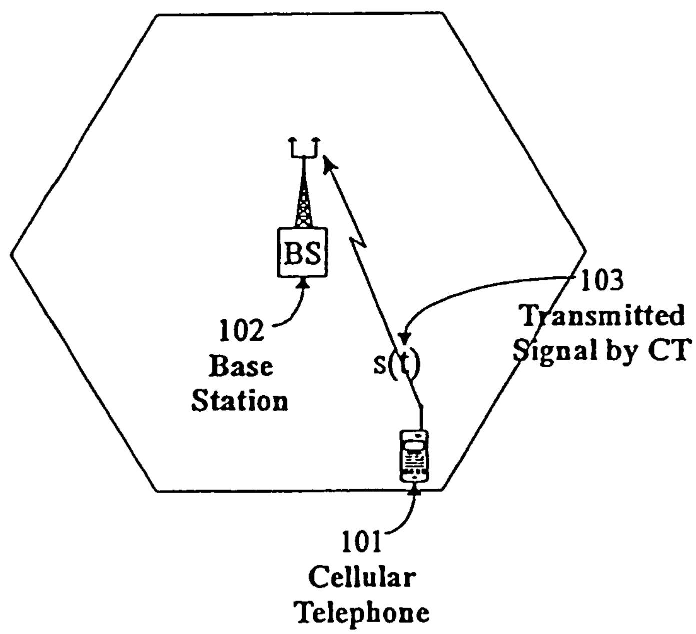
110. Computer readable media comprising instructions for a computer to carry out a wireless location algorithm in which processing of observations of a received signal are weighted according to the received signal strength of the received signal.

111. A host computer programmed to carry out a wireless location algorithm in which processing of observations of a received signal are weighted according to the received signal strength of the received signal.

112. Computer readable media comprising instructions for a computer to carry out a wireless location procedure selected from the group consisting of the procedures I, IA, IB, II, IIA, IIB, III, IIA, IIB, IV, IVA, IVB and V.

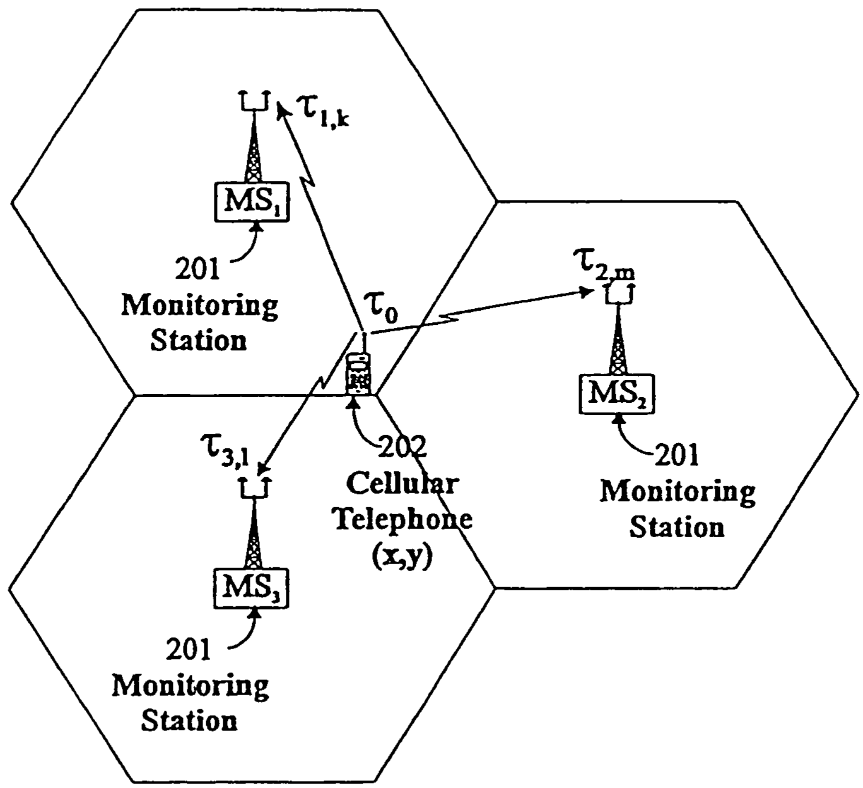
113. A host computer programmed to carry out a wireless location procedure selected from the group consisting of the procedures I, IA, IB, II, IIA, IIB, III, IIA, IIB, IV, IVA, IVB and V.

114. A method of locating a wireless transmitter selected from the group consisting of the procedures I, IA, IB, II, IIA, IIB, III, IIA, IIB, IV, IVA, IVB and V.



BS
102
Base
Station
s(t)
103
Transmitted
Signal by CT
101
Cellular
Telephone

Fig. 1



$\tau_{1,k}$
MS_1
201
Monitoring Station
τ_0
$\tau_{2,m}$
MS_2
201
Monitoring Station
$\tau_{3,1}$
MS_3
202
Cellular Telephone (x,y)
201
Monitoring Station

Fig. 2

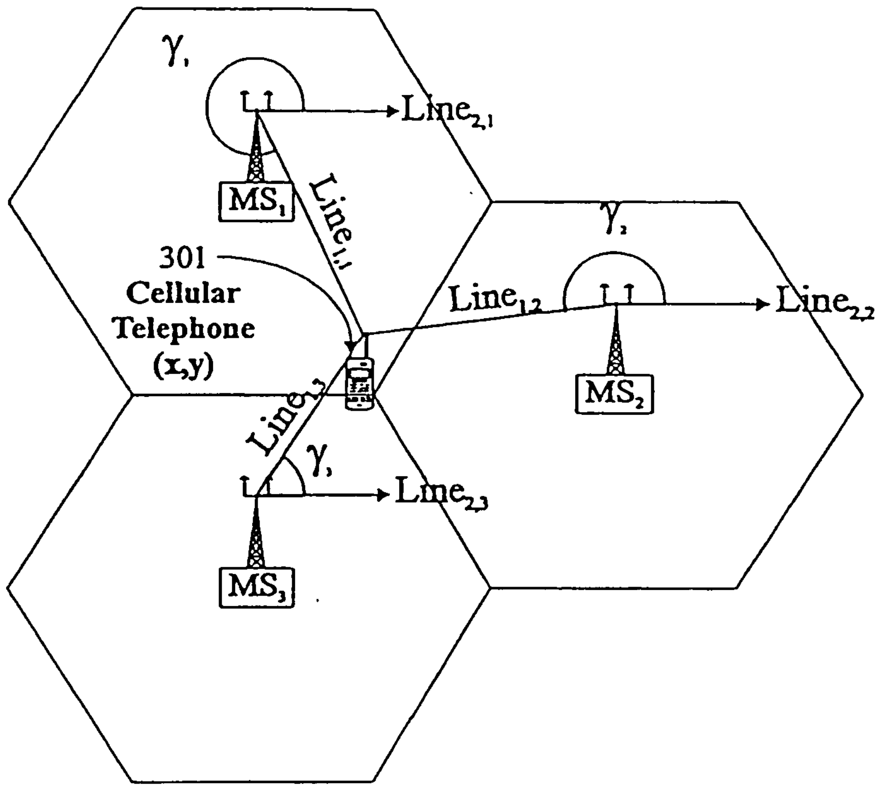
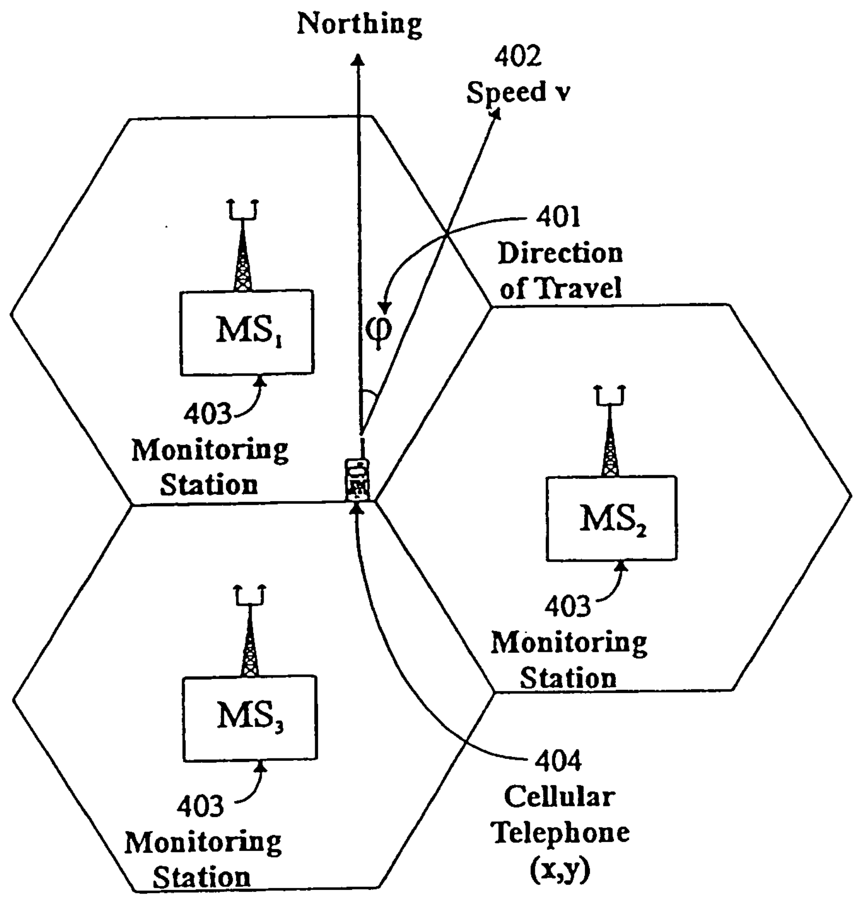
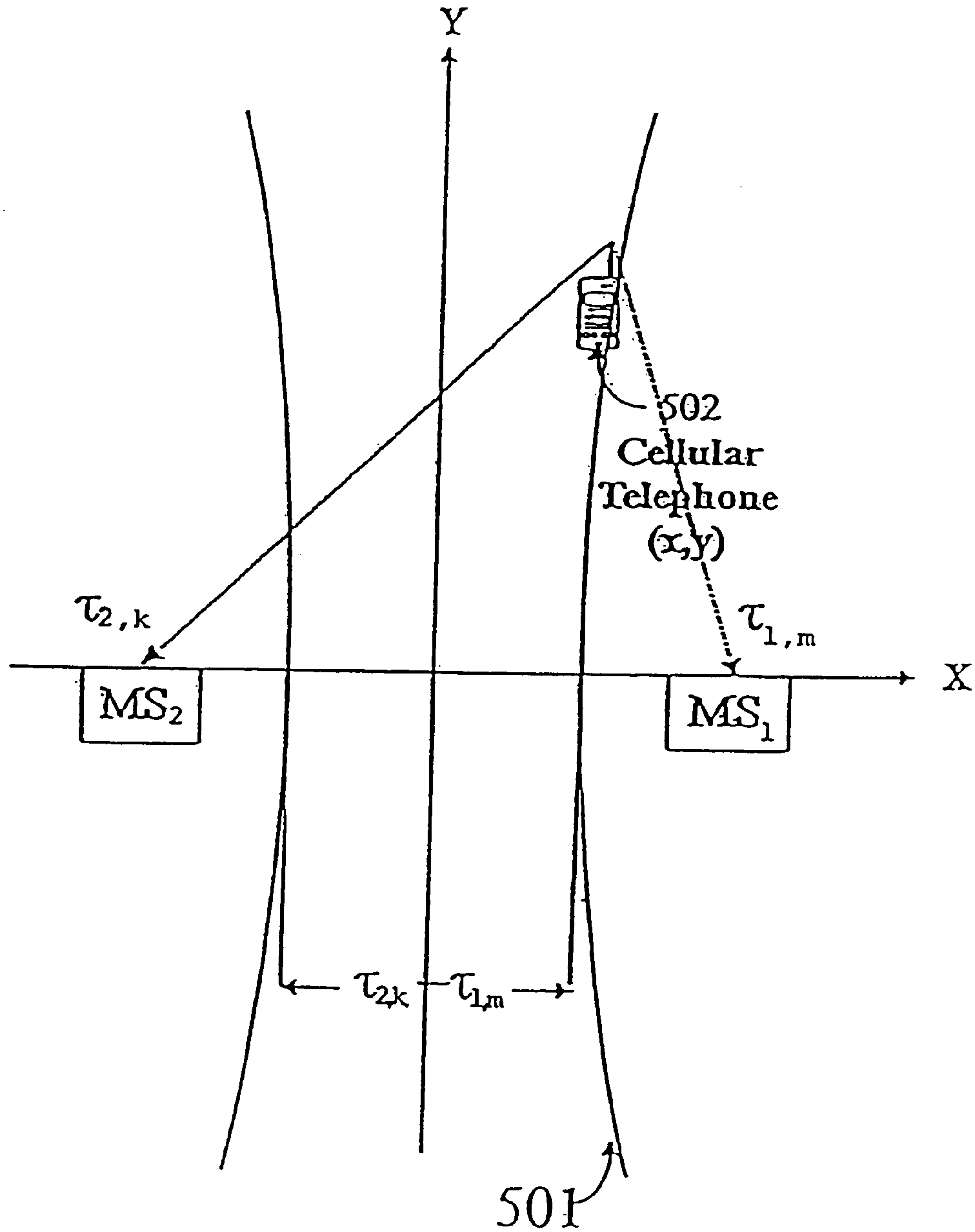

γ_1
Line$_{2,1}$
MS$_1$
Line$_{1,1}$
γ_2
301
Cellular Telephone (x,y)
Line$_{1,2}$
Line$_{2,2}$
MS$_2$
Line$_{1,3}$
γ_3
Line$_{2,3}$
MS$_3$

Fig. 3



Northing
402
Speed v
401
Direction
of Travel
φ
MS1
403
Monitoring
Station
MS2
403
Monitoring
Station
MS3
403
Monitoring
Station
404
Cellular
Telephone
(x,y)

Fig. 4



Trajectory for $TDOA_{2,1,k,m} = \tau_{2,k} - \tau_{1,m}$

Fig. 5

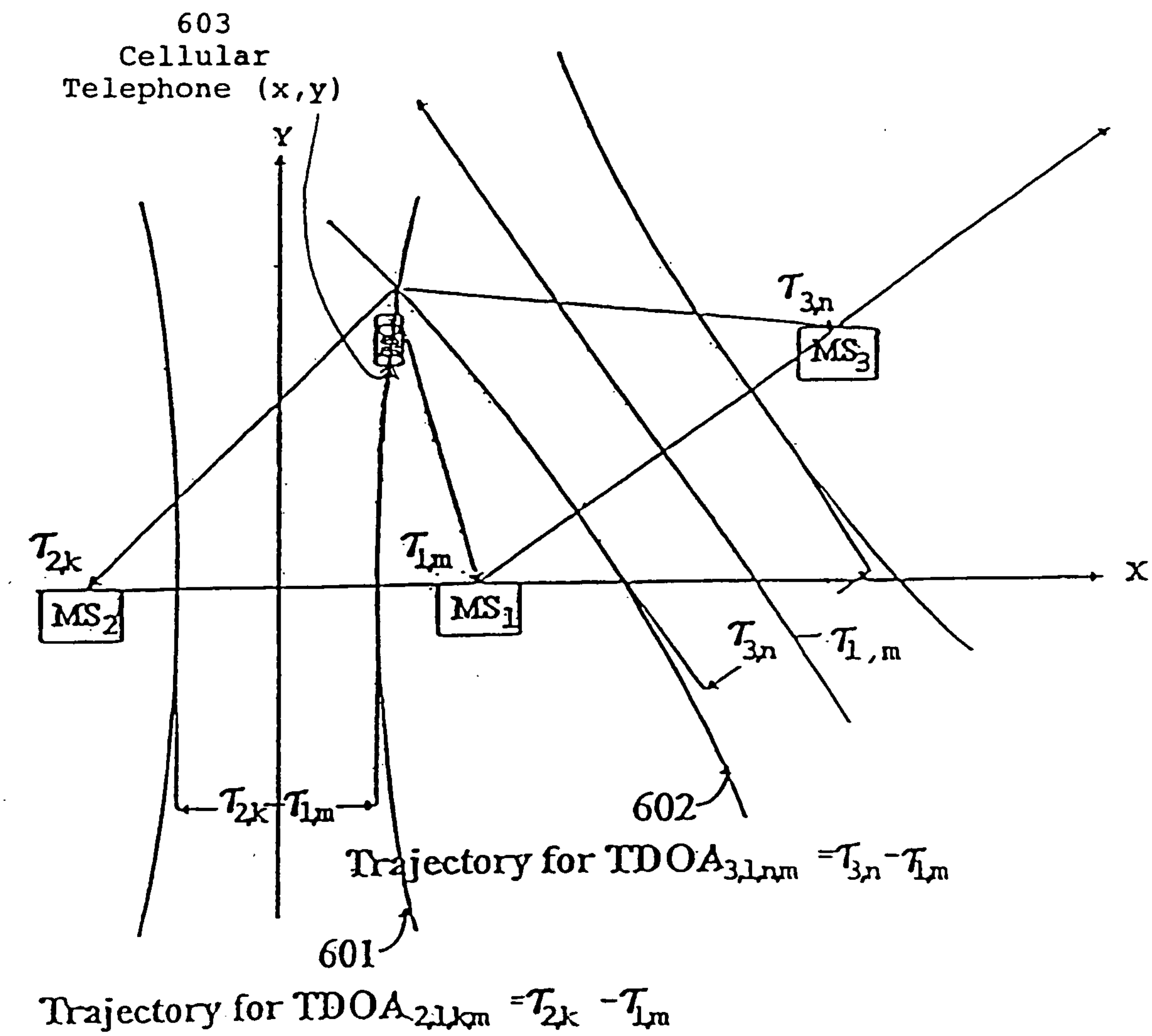
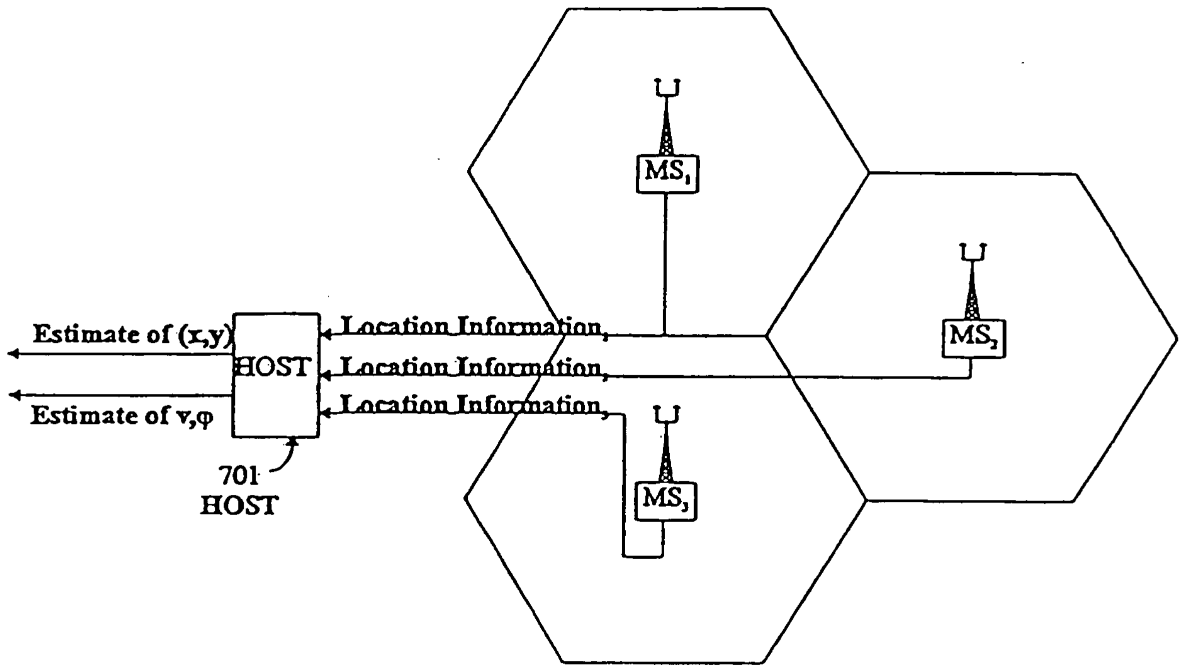
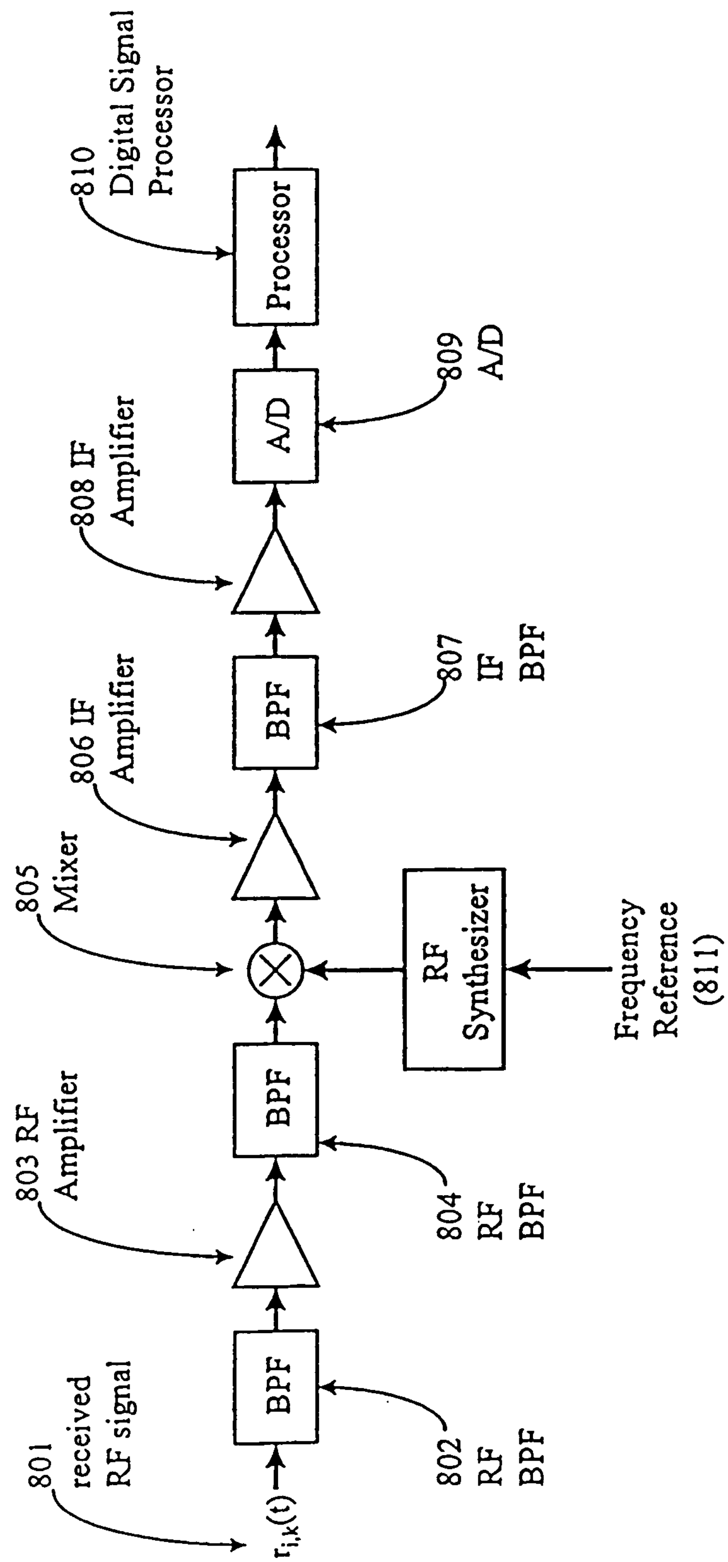

603
Cellular
Telephone (x,y)
Y
X
$\tau_{3,n}$
MS_3
$\tau_{2,k}$
$\tau_{1,m}$
MS_2
MS_1
$\tau_{3,n} - \tau_{1,m}$
$\tau_{2,k} - \tau_{1,m}$
602
Trajectory for $TDOA_{3,1,n,m} = \tau_{3,n} - \tau_{1,m}$
601
Trajectory for $TDOA_{2,1,k,m} = \tau_{2,k} - \tau_{1,m}$

Fig. 6



Estimate of (x,y)
HOST
Estimate of v,φ
701
HOST
Location Information
Location Information
Location Information
MS1
MS2
MS3

Fig. 7



801 received RF signal
$r_{i,k}(t)$
BPF
802 RF BPF
803 RF Amplifier
BPF
804 RF BPF
805 Mixer
RF Synthesizer
Frequency Reference (811)
806 IF Amplifier
BPF
807 IF BPF
808 IF Amplifier
A/D
809 A/D
Processor
810 Digital Signal Processor

Fig. 8

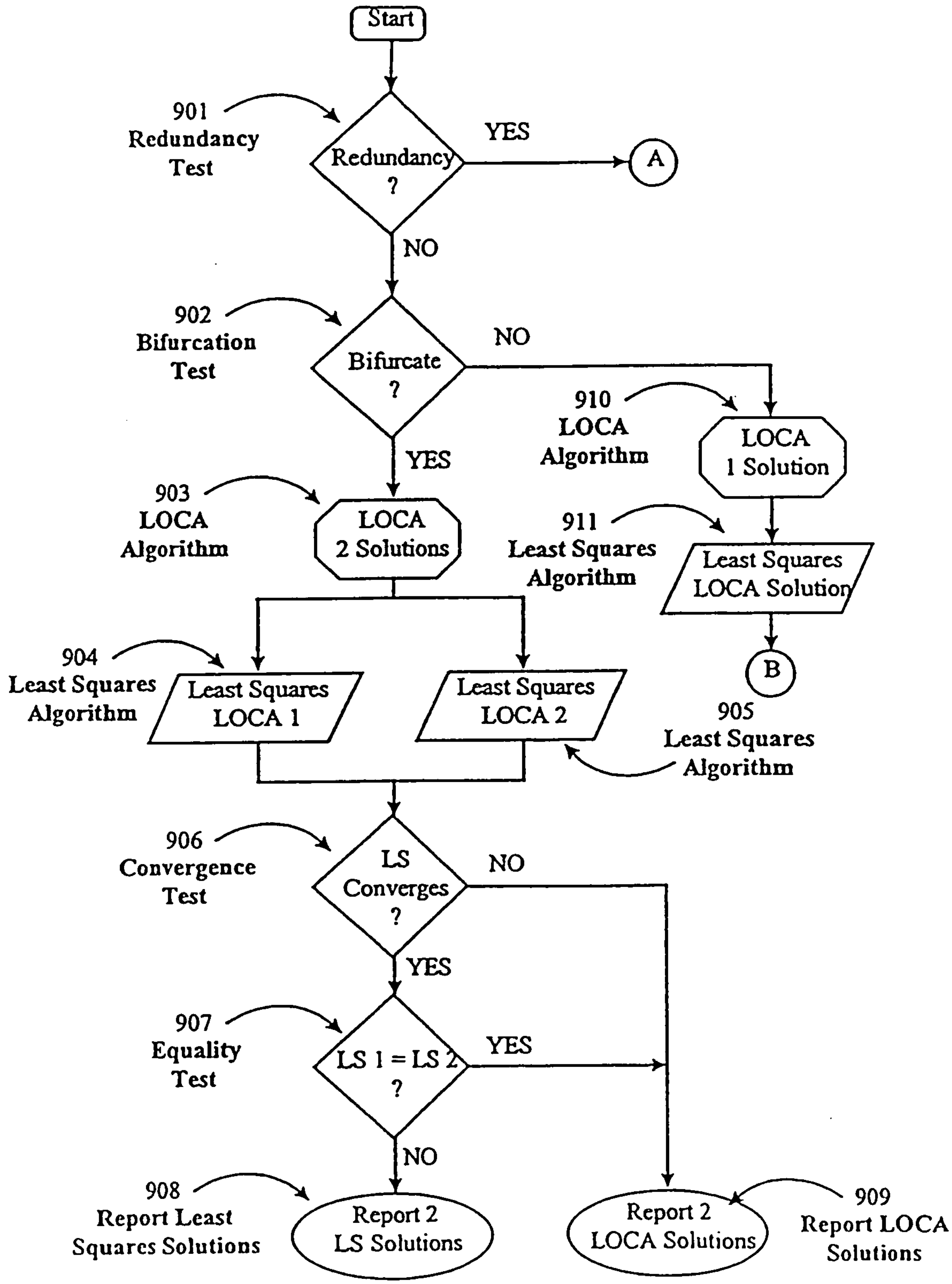

Start
901
Redundancy
Test
Redundancy
?
YES
A
NO
902
Bifurcation
Test
Bifurcate
?
NO
910
LOCA
Algorithm
LOCA
1 Solution
YES
903
LOCA
Algorithm
LOCA
2 Solutions
911
Least Squares
Algorithm
Least Squares
LOCA Solution
B
904
Least Squares
Algorithm
Least Squares
LOCA 1
Least Squares
LOCA 2
905
Least Squares
Algorithm
906
Convergence
Test
LS
Converges
?
NO
YES
907
Equality
Test
LS 1 = LS 2
?
YES
NO
908
Report Least
Squares Solutions
Report 2
LS Solutions
Report 2
LOCA Solutions
909
Report LOCA
Solutions

Fig. 9a

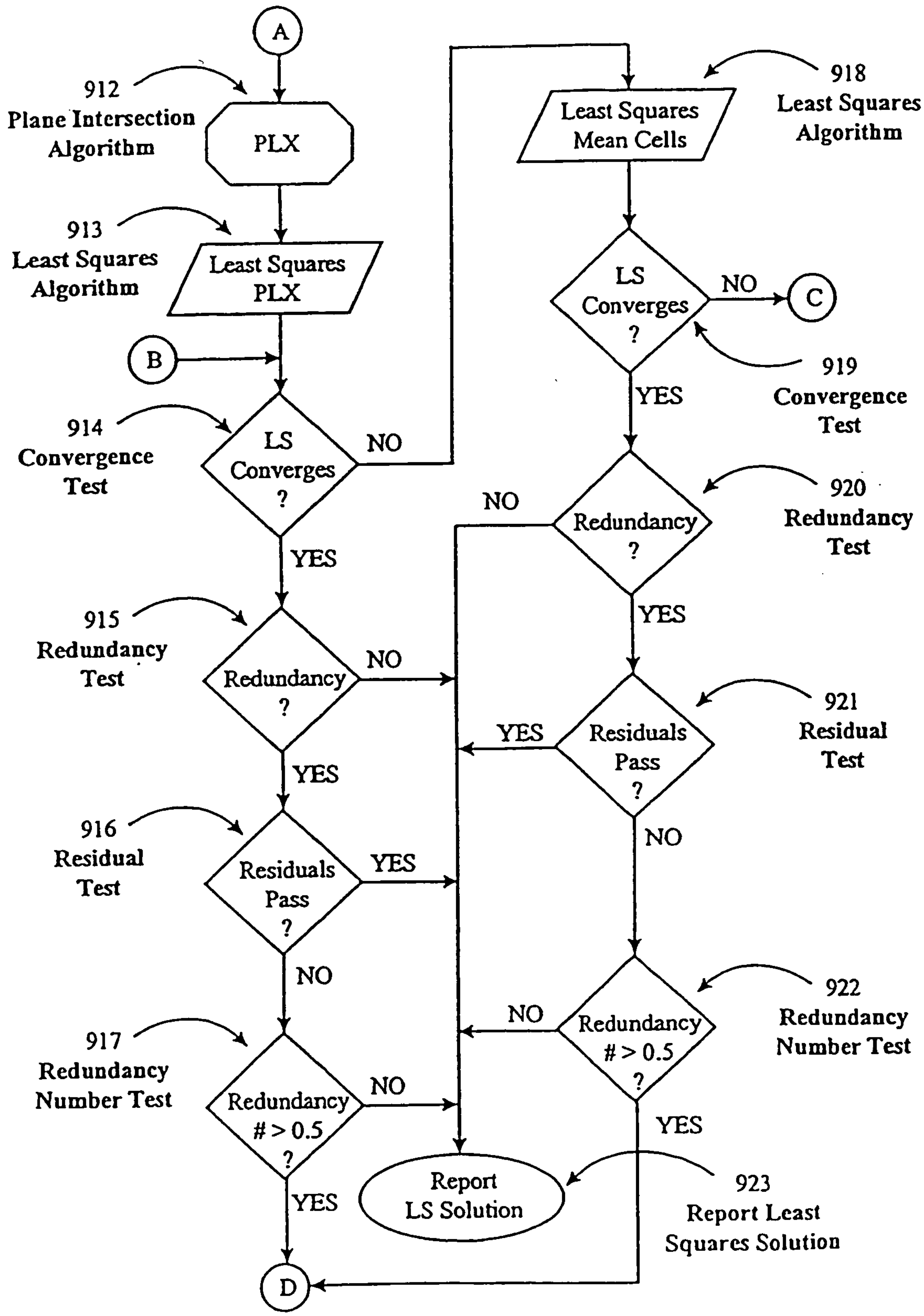

A
912
Plane Intersection
Algorithm
PLX
913
Least Squares
Algorithm
Least Squares
PLX
B
914
Convergence
Test
LS
Converges
?
NO
YES
915
Redundancy
Test
Redundancy
?
NO
YES
916
Residual
Test
Residuals
Pass
?
YES
NO
917
Redundancy
Number Test
Redundancy
> 0.5
?
NO
YES
D
918
Least Squares
Algorithm
Least Squares
Mean Cells
LS
Converges
?
NO
C
919
Convergence
Test
YES
920
Redundancy
Test
Redundancy
?
NO
YES
921
Residual
Test
Residuals
Pass
?
YES
NO
922
Redundancy
Number Test
Redundancy
> 0.5
?
NO
YES
Report
LS Solution
923
Report Least
Squares Solution

Fig. 9b

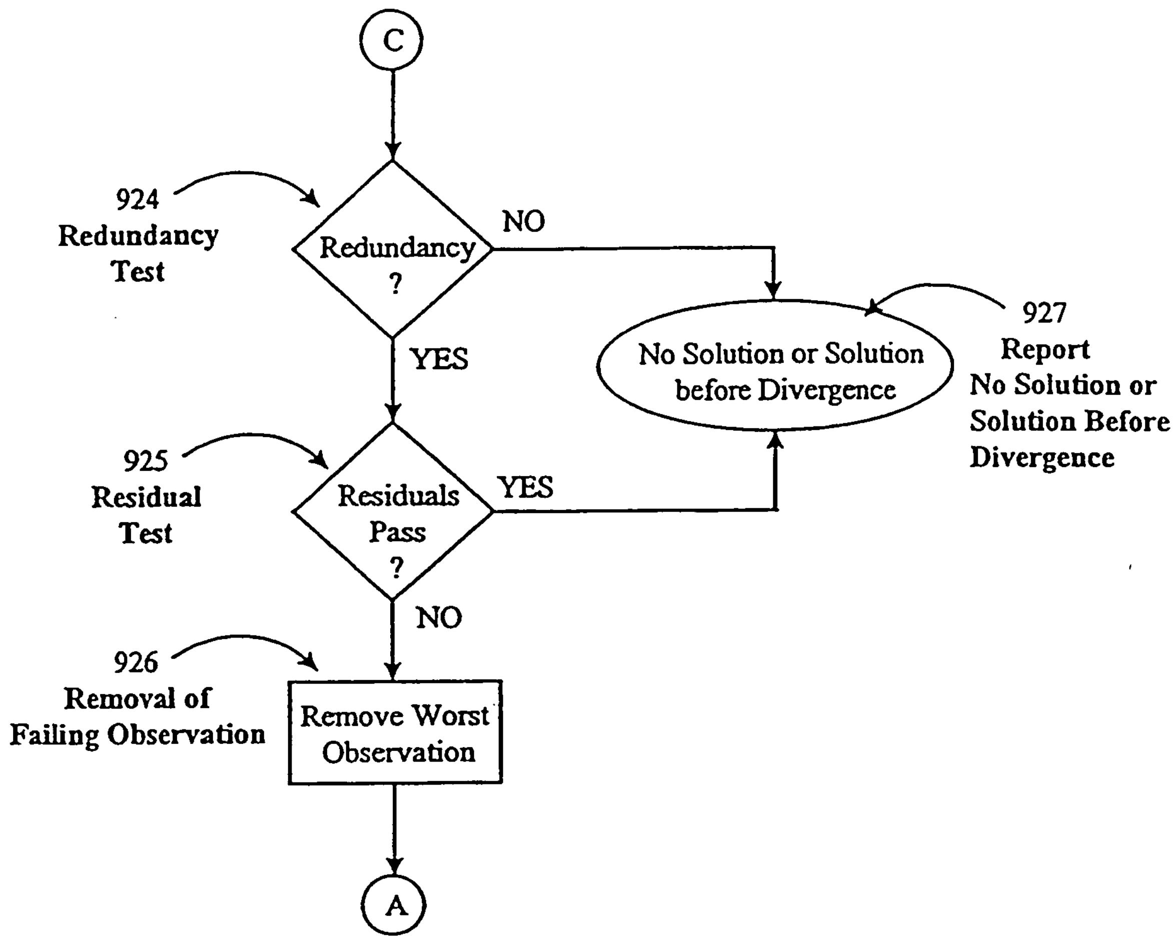

C
924
Redundancy
Test
Redundancy
?
NO
YES
No Solution or Solution
before Divergence
927
Report
No Solution or
Solution Before
Divergence
925
Residual
Test
Residuals
Pass
?
YES
NO
926
Removal of
Failing Observation
Remove Worst
Observation
A

Fig. 9c

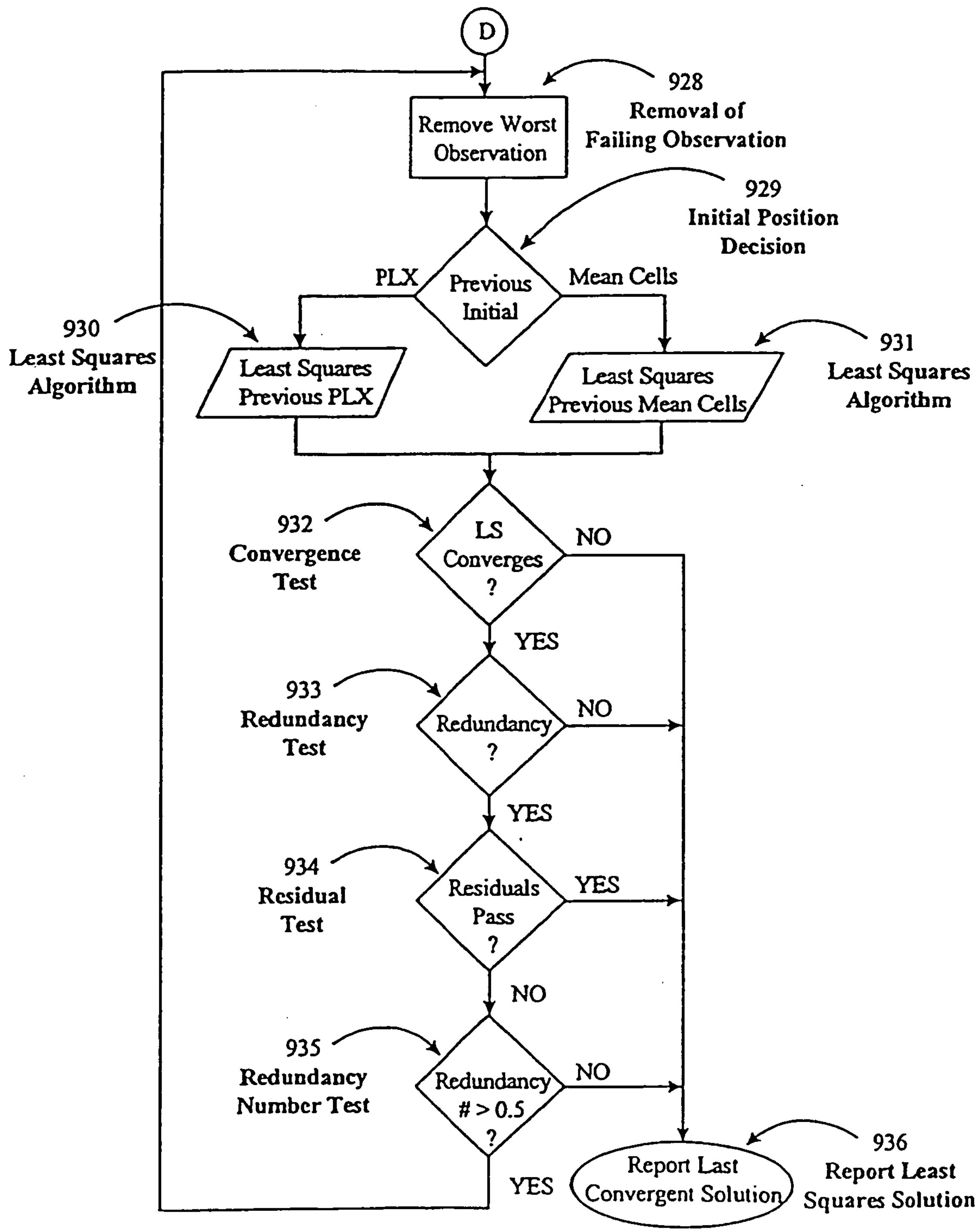

D
928
Removal of
Failing Observation
Remove Worst
Observation
929
Initial Position
Decision
PLX
Previous
Initial
Mean Cells
930
Least Squares
Algorithm
Least Squares
Previous PLX
Least Squares
Previous Mean Cells
931
Least Squares
Algorithm
932
Convergence
Test
LS
Converges
?
NO
YES
933
Redundancy
Test
Redundancy
?
NO
YES
934
Residual
Test
Residuals
Pass
?
YES
NO
935
Redundancy
Number Test
Redundancy
> 0.5
?
NO
YES
Report Last
Convergent Solution
936
Report Least
Squares Solution

Fig. 9d

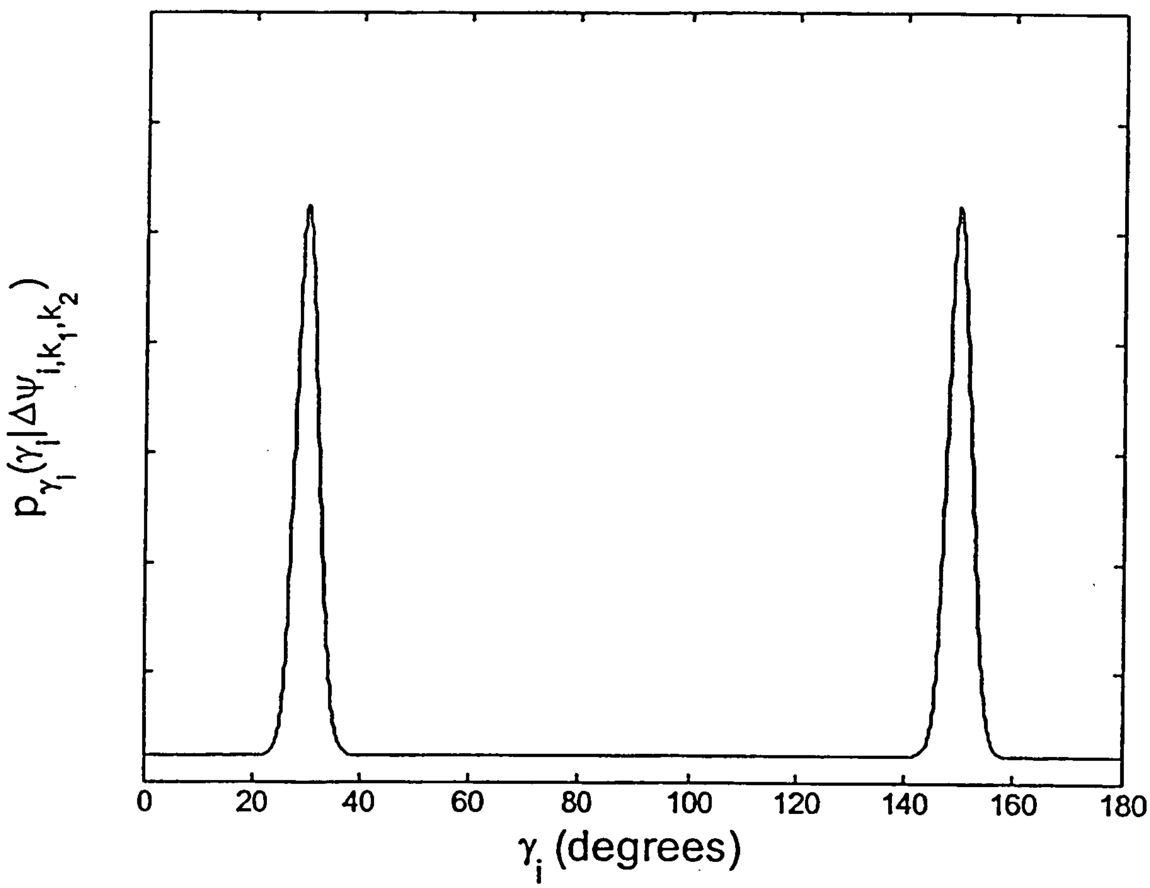
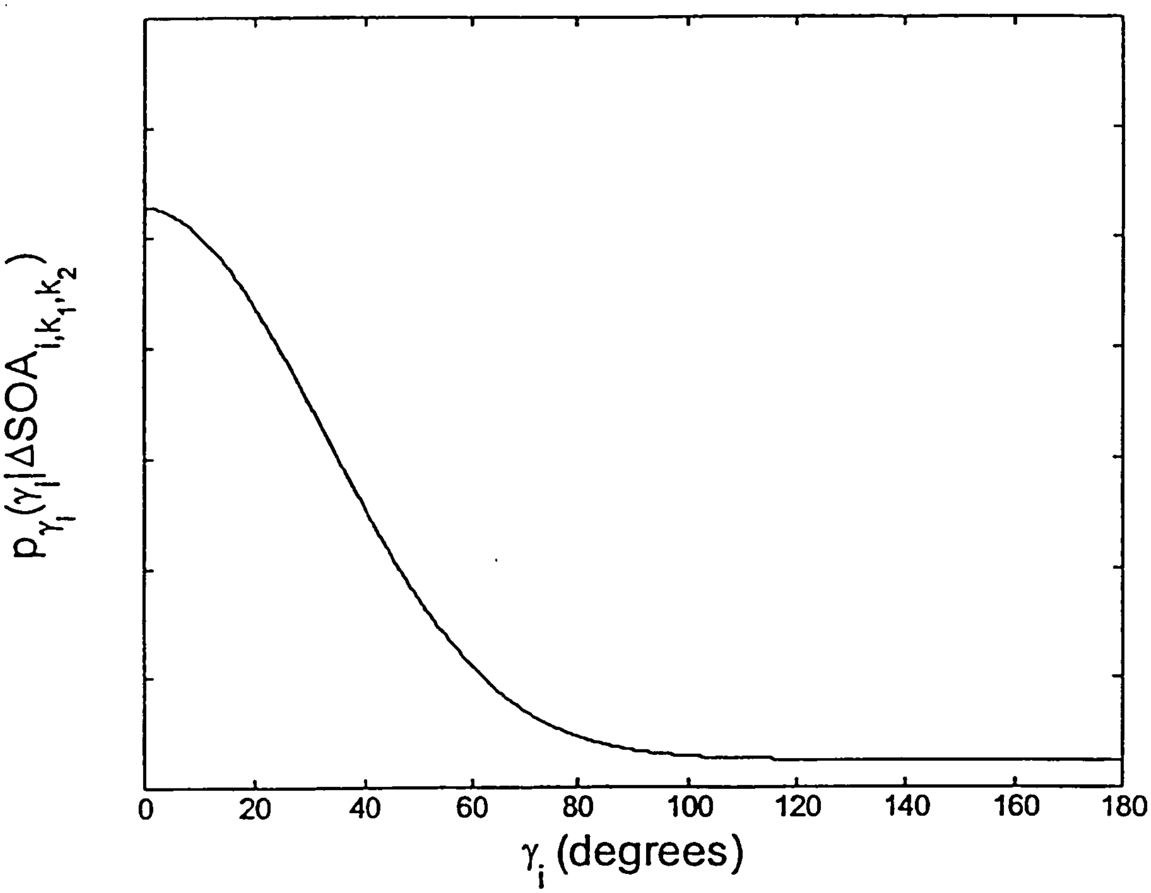

$p_{\gamma_l}(\gamma_l|\Delta\psi_{l,k_1,k_2})$
0
20
40
60
80
100
120
140
160
180
γ_i (degrees)

Fig. 10



$p_{\gamma_i}(\gamma_i|\Delta SOA_{i,k_1,k_2})$
0
20
40
60
80
100
120
140
160
180
γ_i (degrees)

Fig. 11

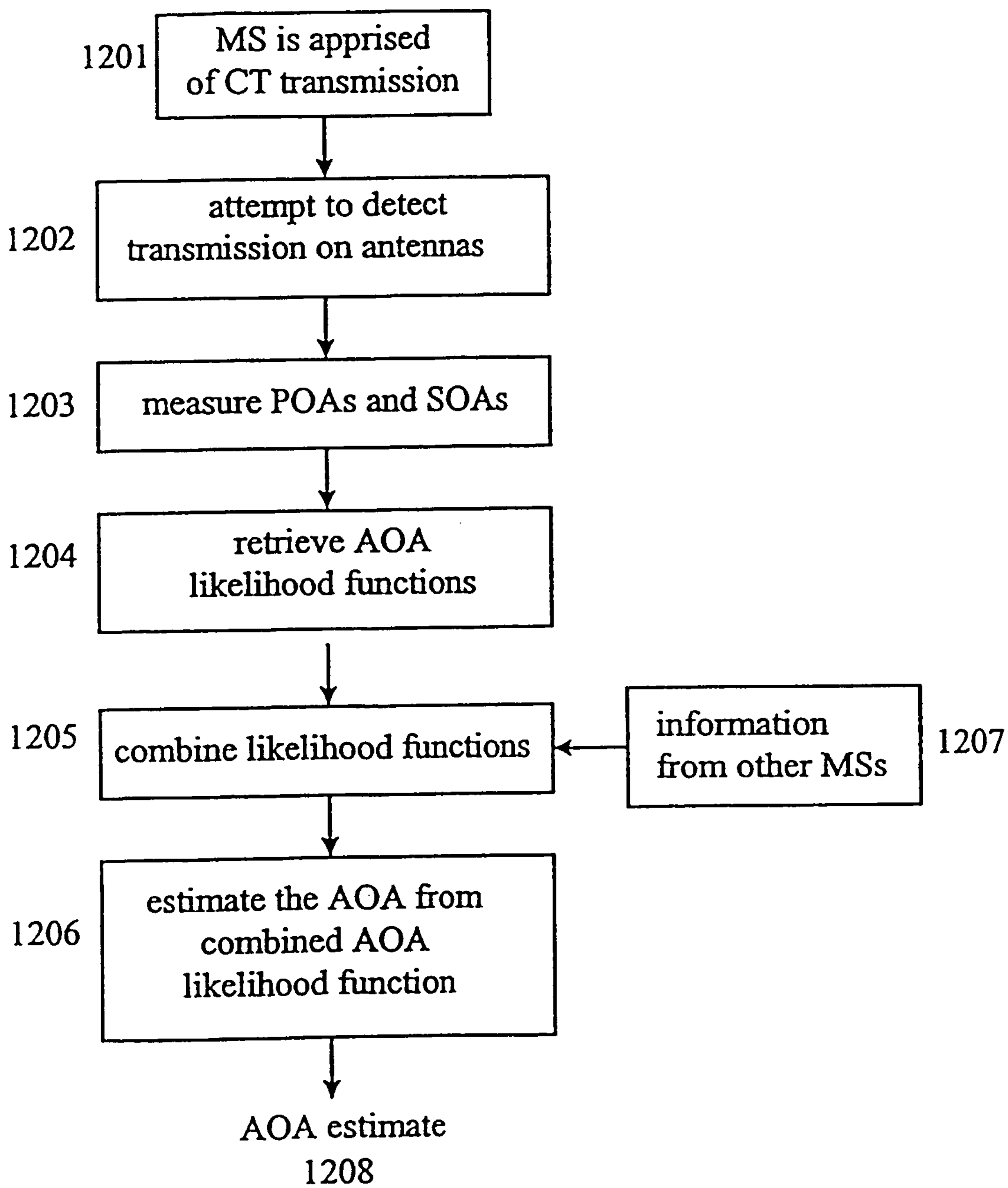

1201
MS is apprised of CT transmission
1202
attempt to detect transmission on antennas
1203
measure POAs and SOAs
1204
retrieve AOA likelihood functions
1205
combine likelihood functions
information from other MSs
1207
1206
estimate the AOA from combined AOA likelihood function
AOA estimate
1208

Fig. 12

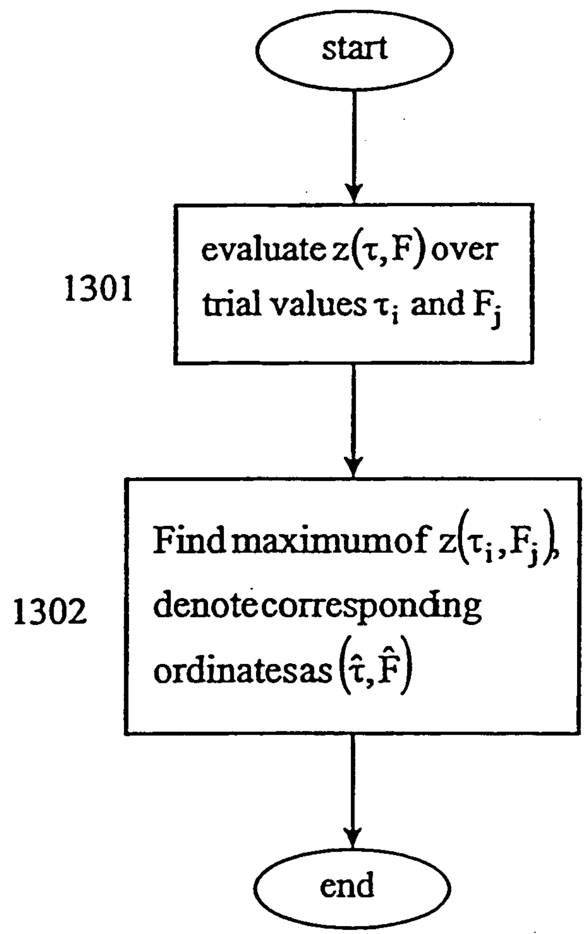

start
evaluate $z(\tau, F)$ over trial values τ_i and F_j
1301
Find maximum of $z(\tau_i, F_j)$, denote corresponding ordinates as $(\hat{\tau}, \hat{F})$
1302
end

Fig. 13

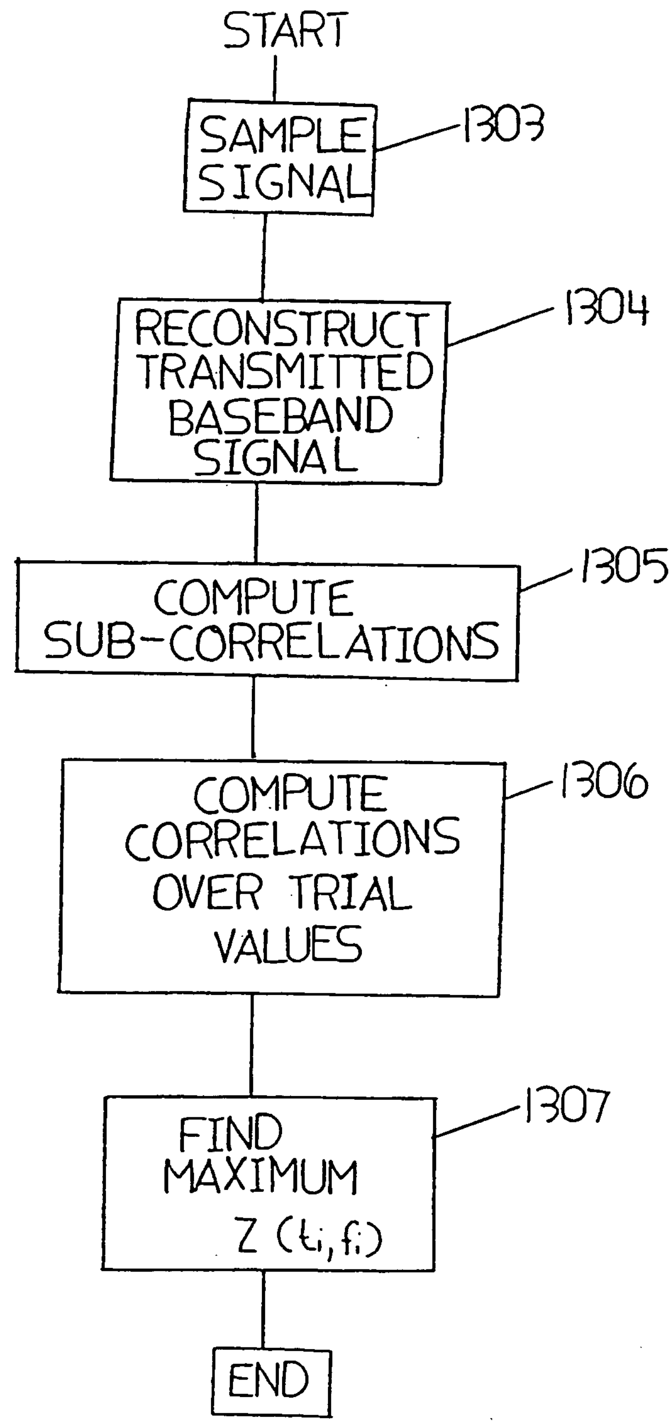

START
SAMPLE SIGNAL
1303
RECONSTRUCT TRANSMITTED BASEBAND SIGNAL
1304
COMPUTE SUB-CORRELATIONS
1305
COMPUTE CORRELATIONS OVER TRIAL VALUES
1306
FIND MAXIMUM Z (ti, fi)
1307
END

FIGURE 13A

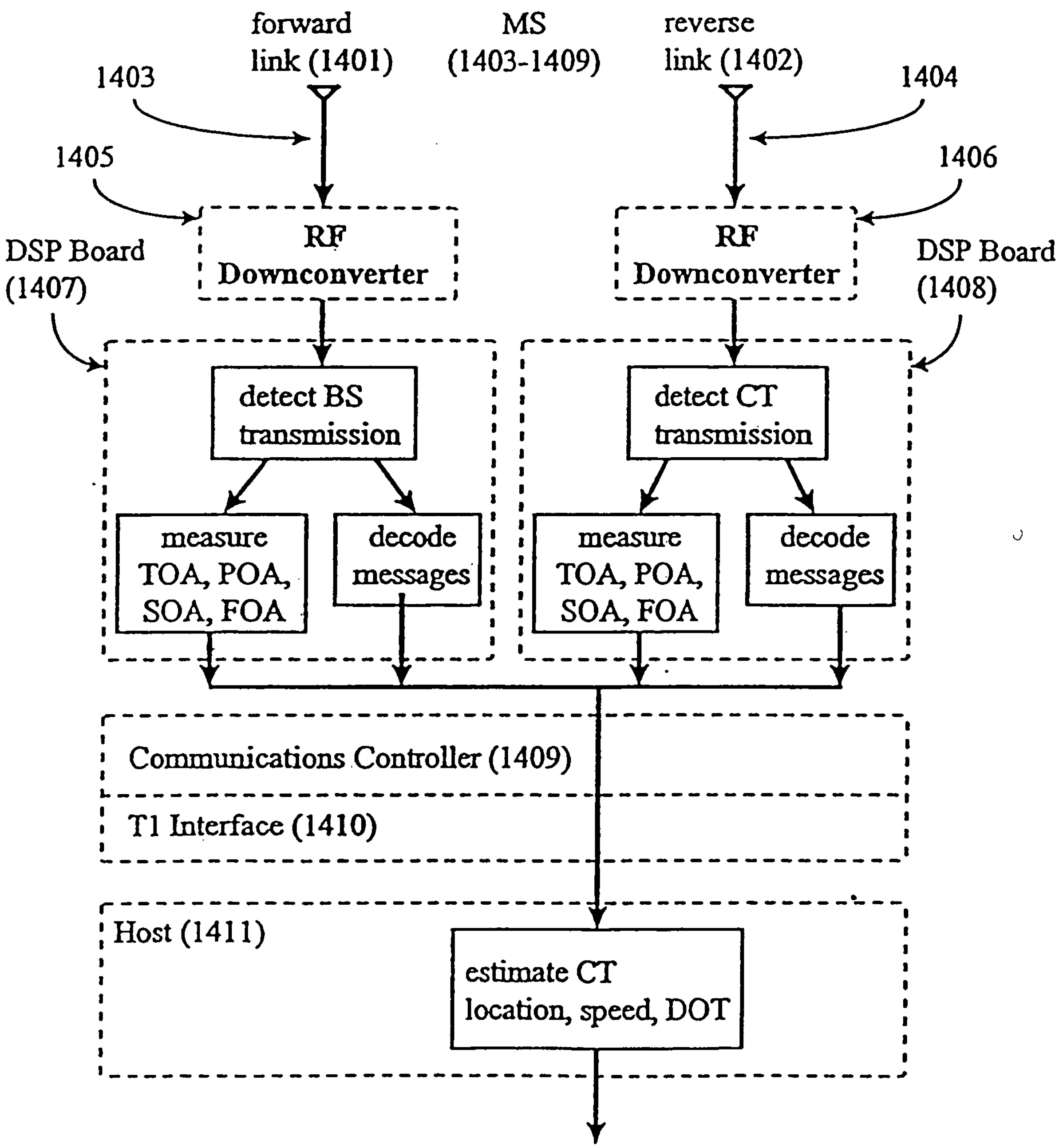
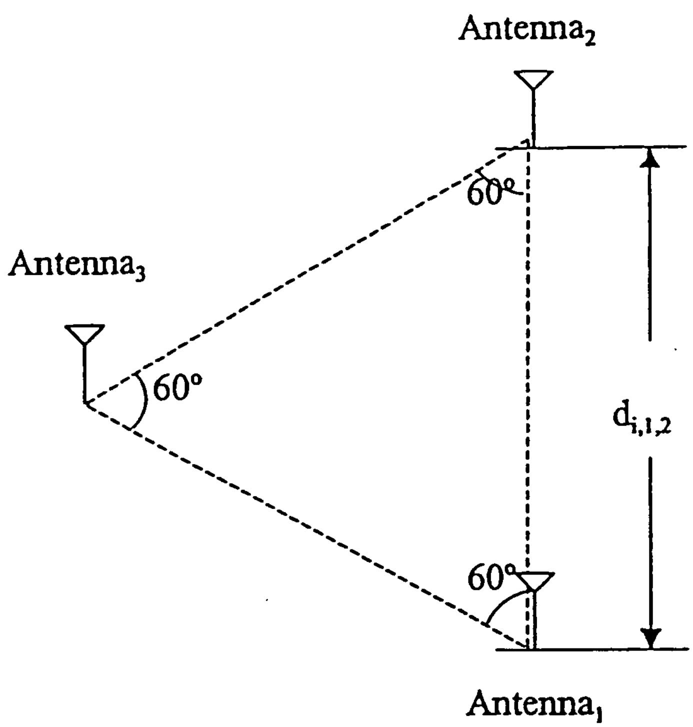

forward
link (1401)
MS
(1403-1409)
reverse
link (1402)
1403
1404
1405
1406
RF
Downconverter
RF
Downconverter
DSP Board
(1407)
DSP Board
(1408)
detect BS
transmission
detect CT
transmission
measure
TOA, POA,
SOA, FOA
decode
messages
measure
TOA, POA,
SOA, FOA
decode
messages
Communications Controller (1409)
T1 Interface (1410)
Host (1411)
estimate CT
location, speed, DOT

Fig. 14


Antenna$_2$
60°
Antenna$_3$
60°
$d_{i,1,2}$
60°
Antenna$_1$

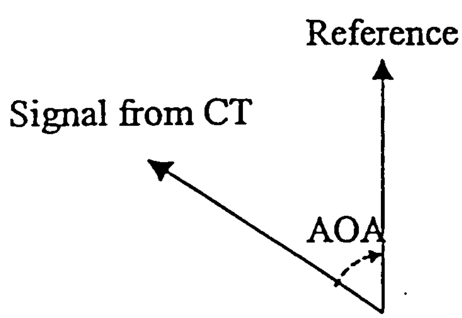

Reference
Signal from CT
AOA

Fig. 15

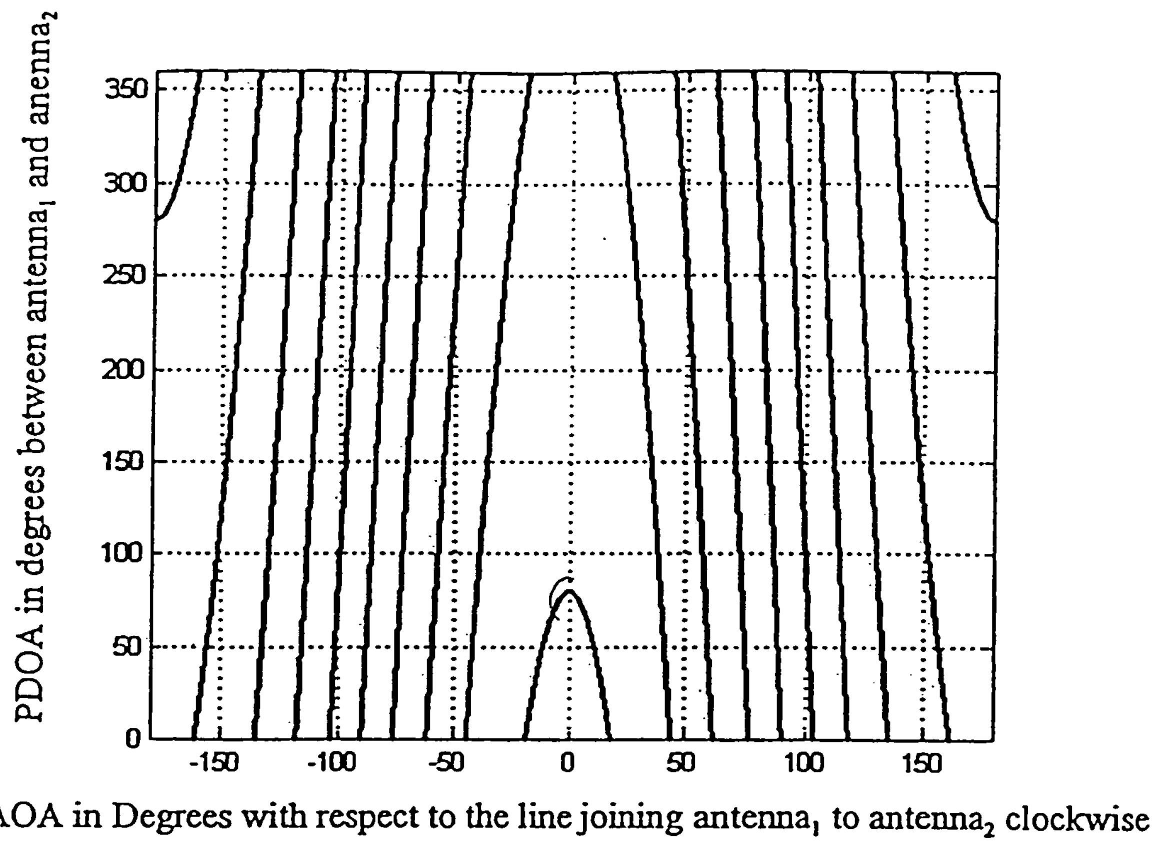

PDOA in degrees between antenna1 and anenna2
350
300
250
200
150
100
50
0
-150
-100
-50
0
50
100
150
AOA in Degrees with respect to the line joining antenna1 to antenna2 clockwise

Fig. 16a

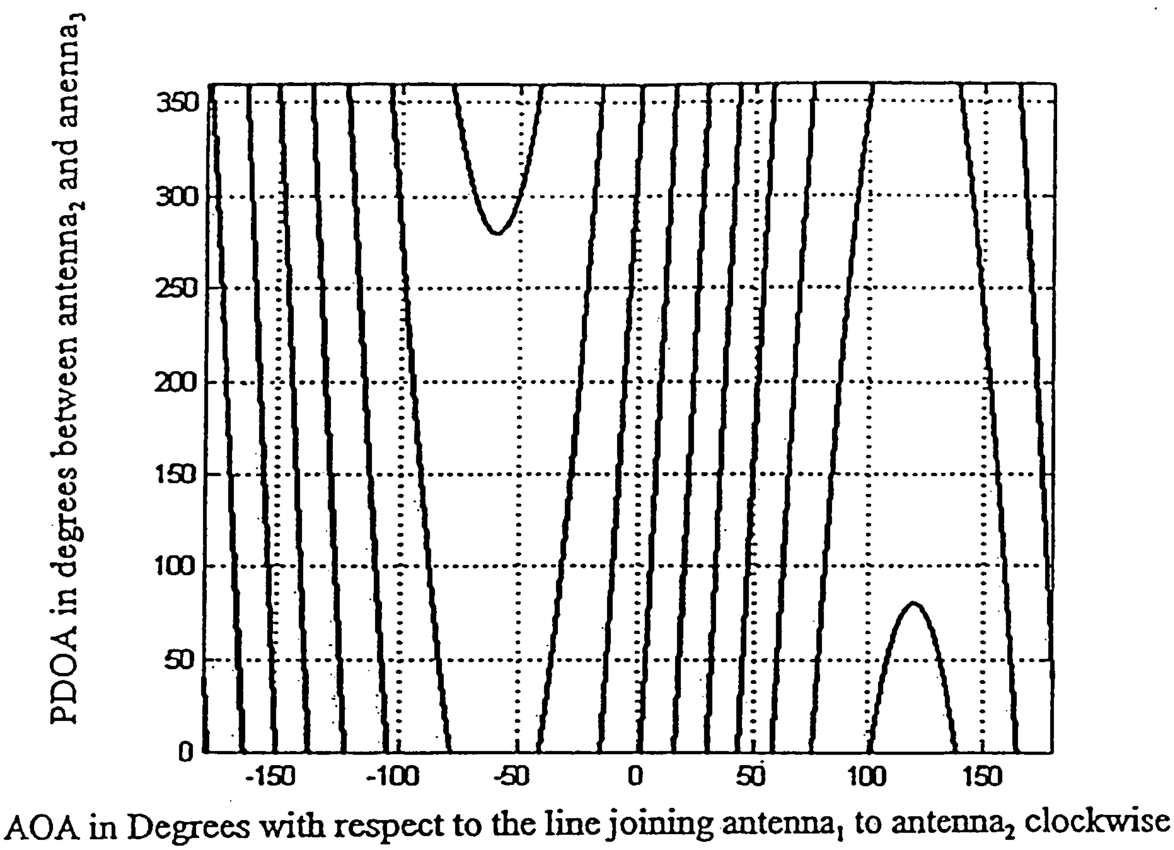
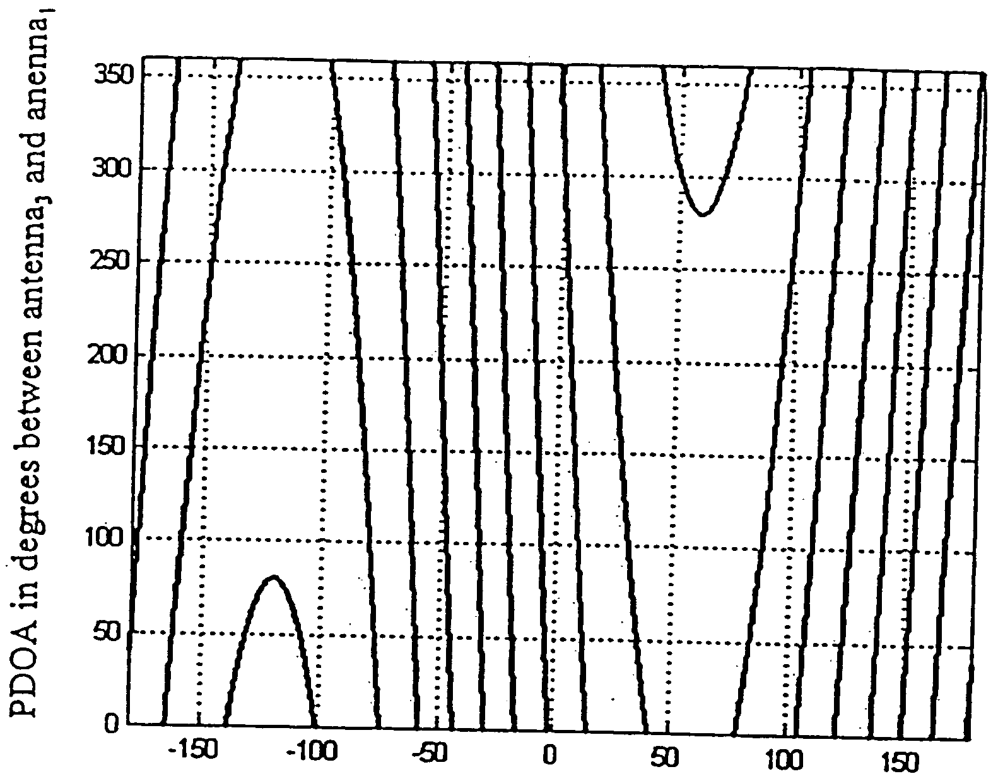
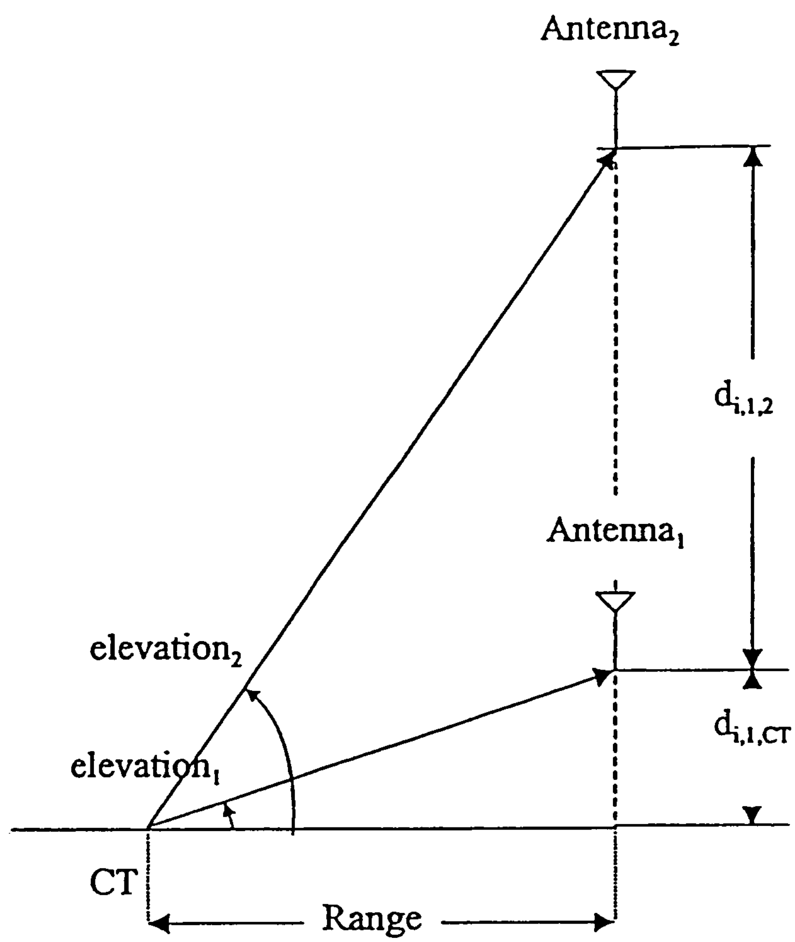

PDOA in degrees between antenna2 and anenna3
350
300
250
200
150
100
50
0
-150
-100
-50
0
50
100
150
AOA in Degrees with respect to the line joining antenna1 to antenna2 clockwise

Fig. 16b



AOA in Degrees with respect to the line joining antenna$_1$ to antenna$_2$ clockwise

Fig. 16c



Antenna$_2$
$d_{i,1,2}$
Antenna$_1$
elevation$_2$
$d_{i,1,CT}$
elevation$_1$
CT
Range

Fig. 17

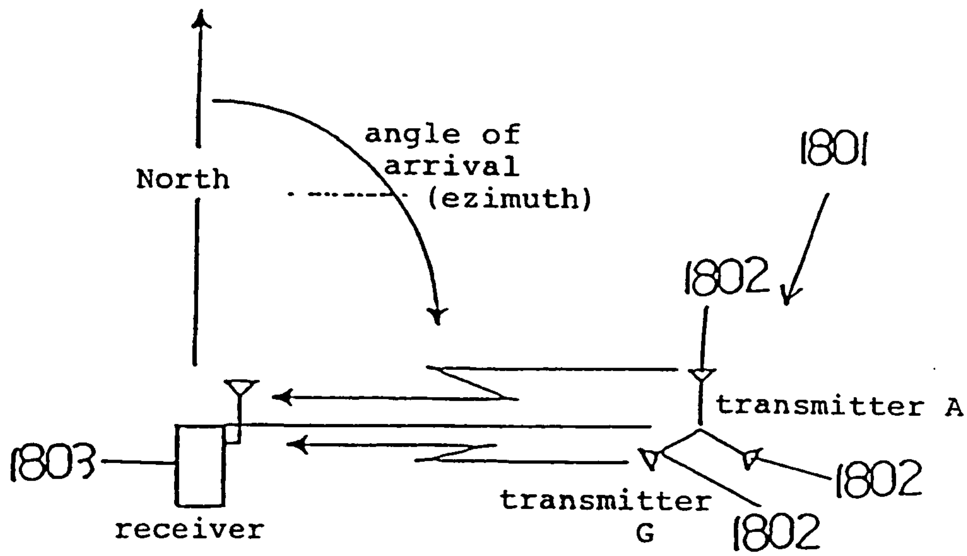


FIGURE 18

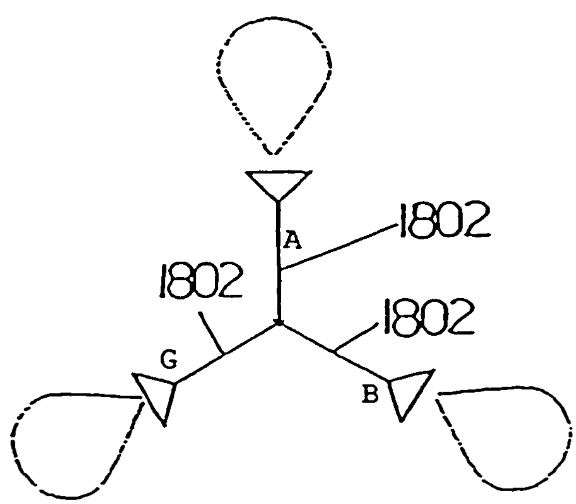


FIGURE 19

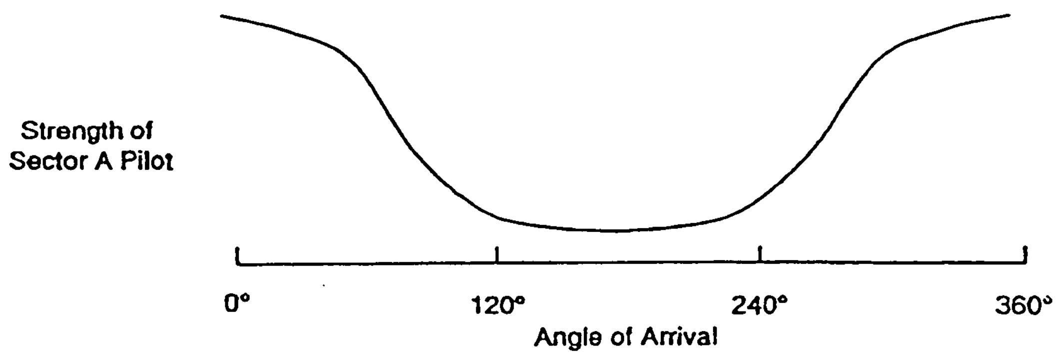


FIGURE 20A

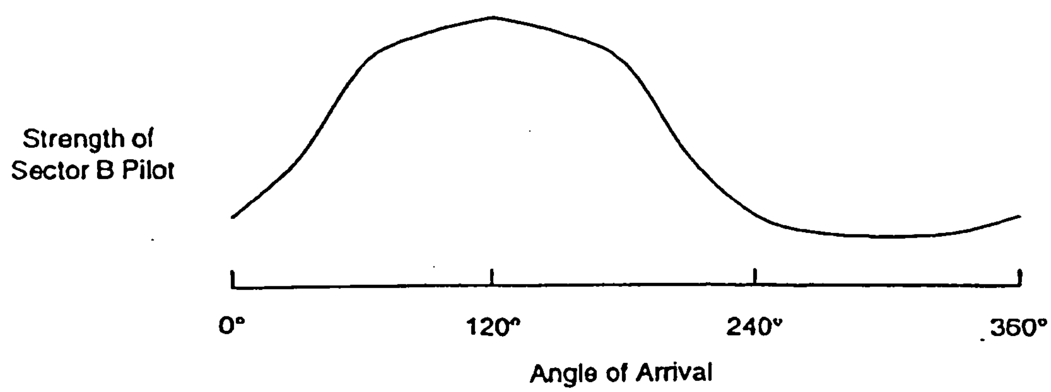


FIGURE 20B

FIGURE 21

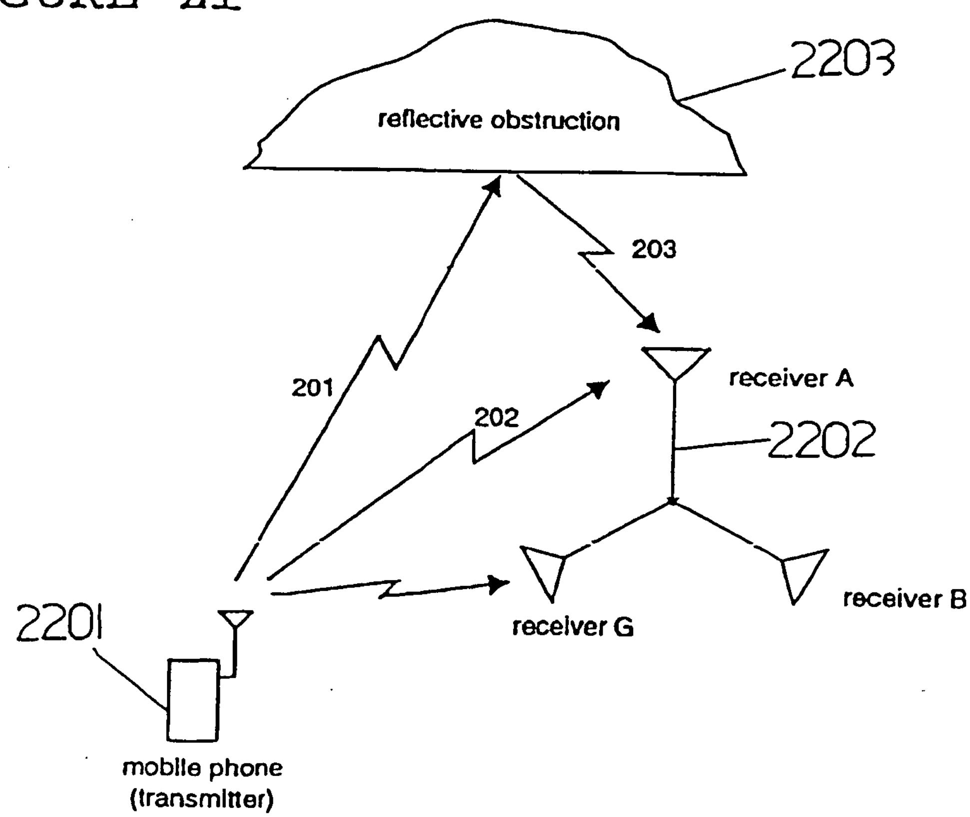
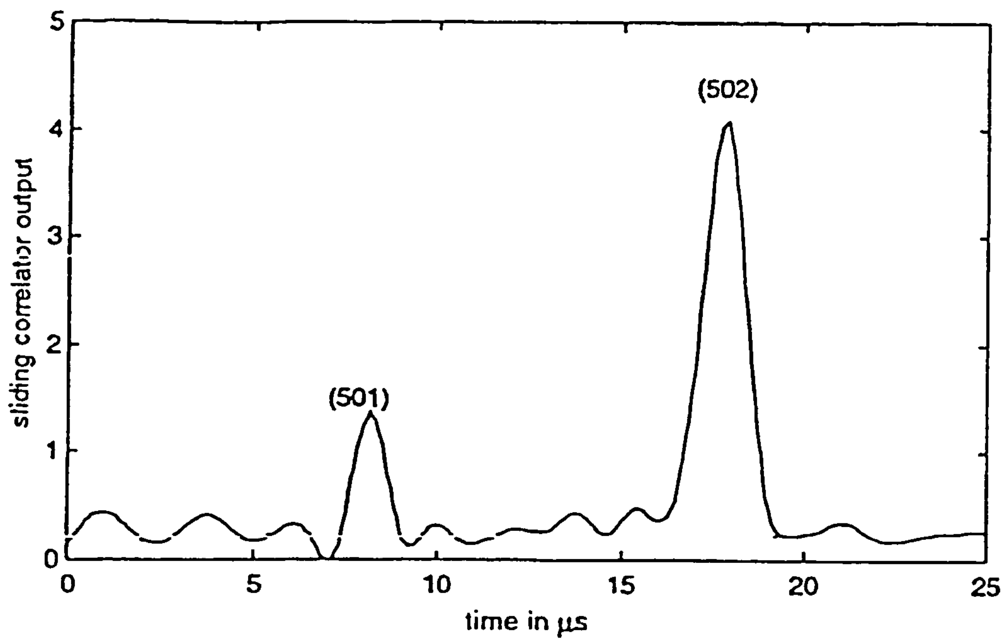


FIGURE 22



(502)
(501)
sliding correlator output
time in μs
0
1
2
3
4
5
0
5
10
15
20
25

FIGURE 23

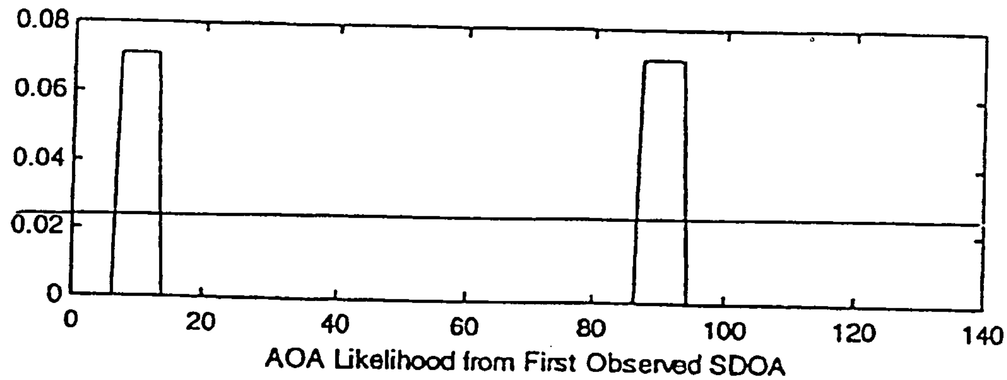


FIGURE 24A

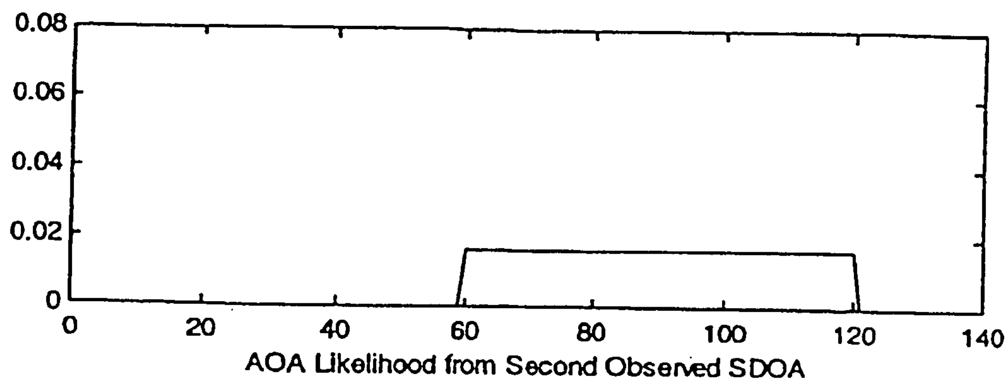


FIGURE 24B

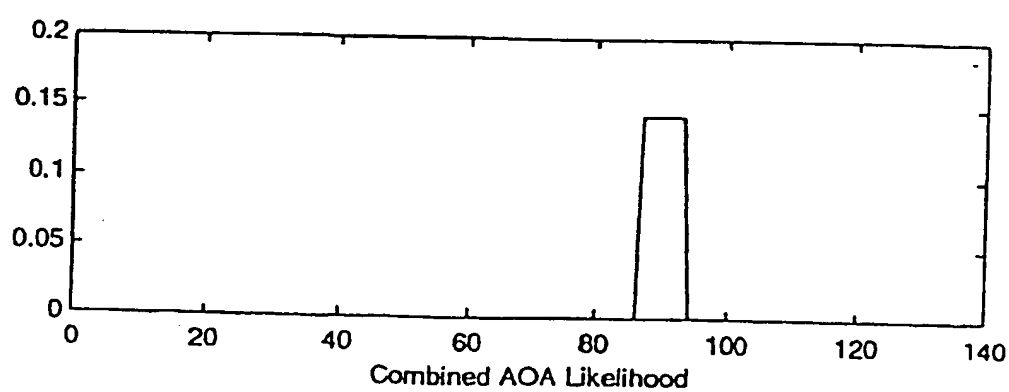


FIGURE 24C

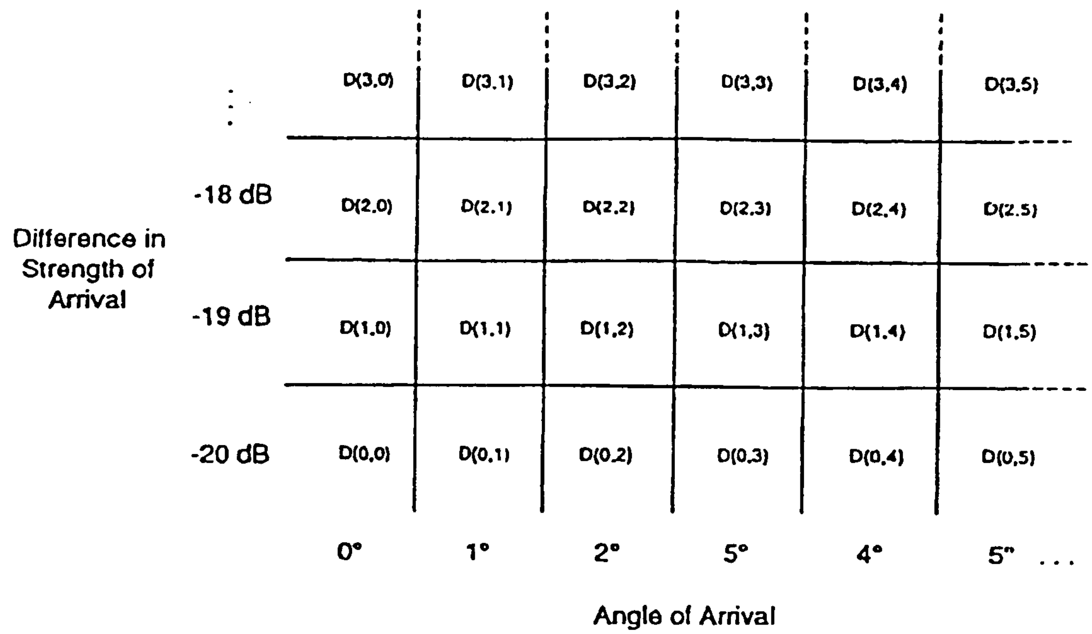


FIGURE 25

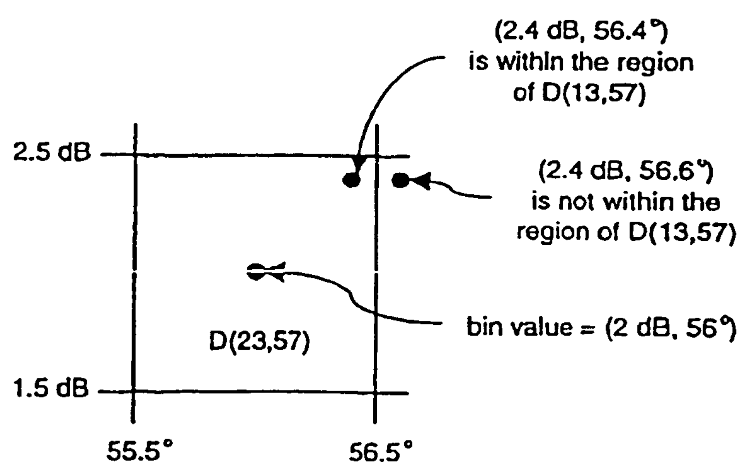


FIGURE 26

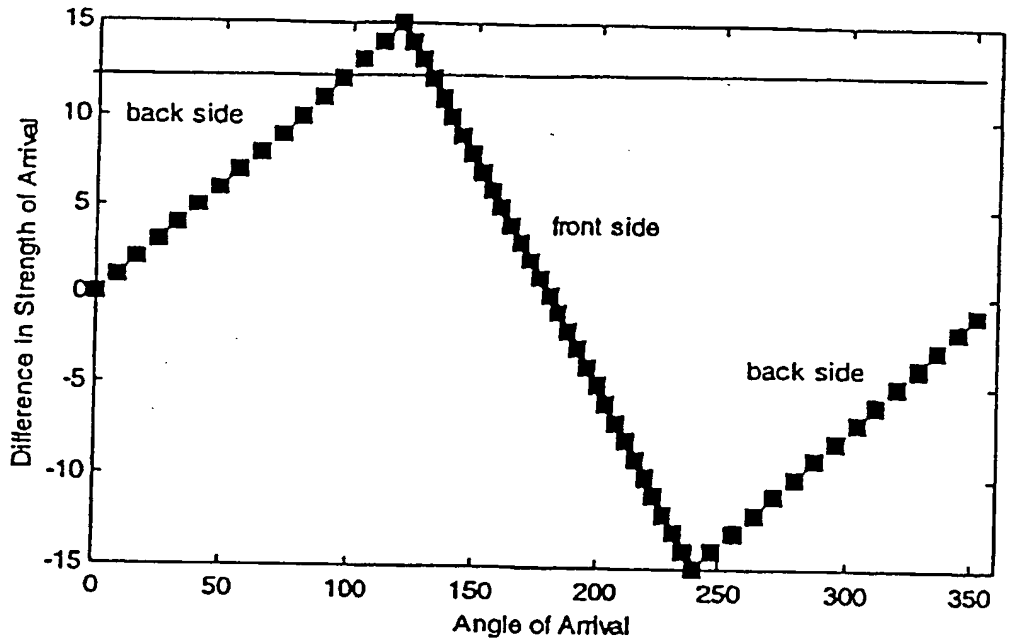


FIGURE 27

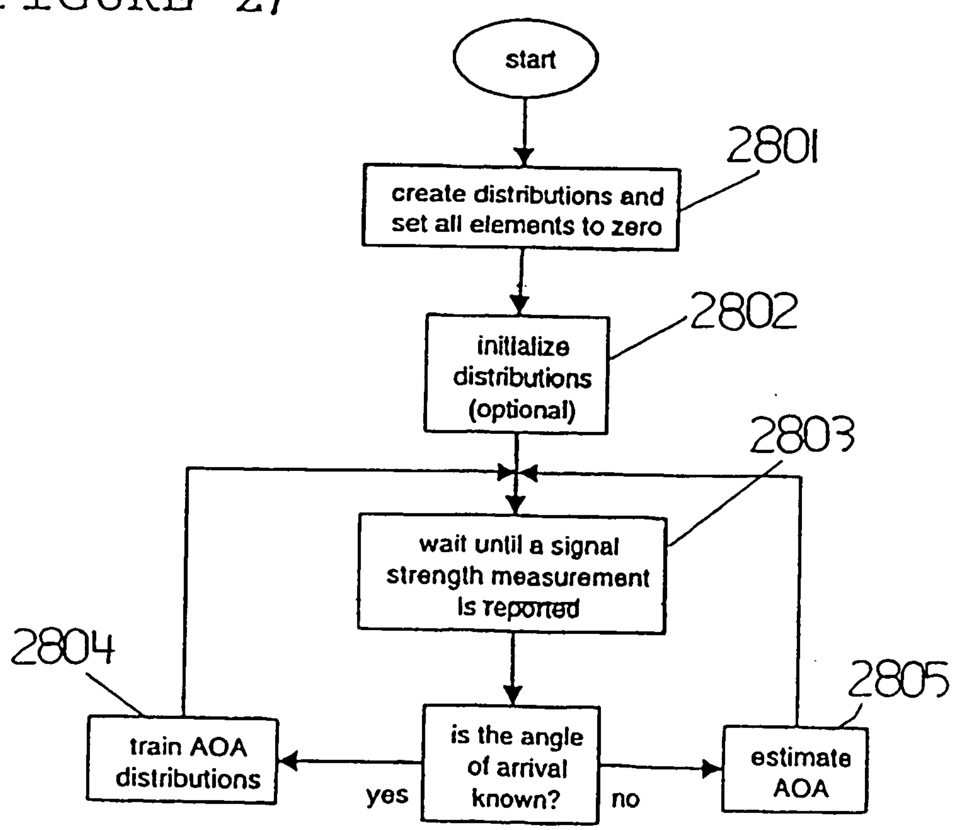
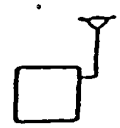
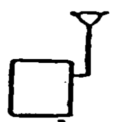


FIGURE 28

5	0	-4	-5	-10	-7	-13	-21
4	-2	-1	-3	-2	-9	-12	-18
4	5	1	1	-3	-8	-10	-14
5	8	1	2	-2	-8	-6	-12
11	6	5	-2	2	-4	-8	-10
11	8	4	2	-4	-4	-4	-4
12	8	6	3	1	0	-5	-9
14	11	3	3	1	0	-4	-1
12	7	8	4	3	-1	-2	-1



Receiver 2



Receiver 1

FIGURE 29

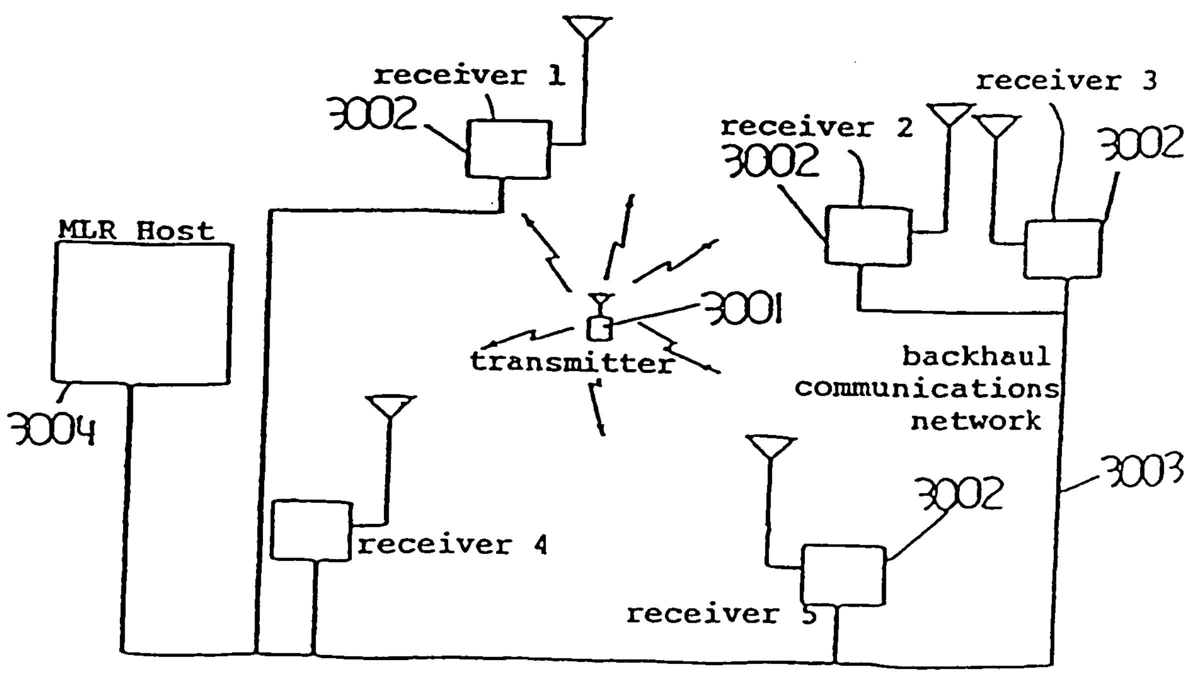


FIGURE 30

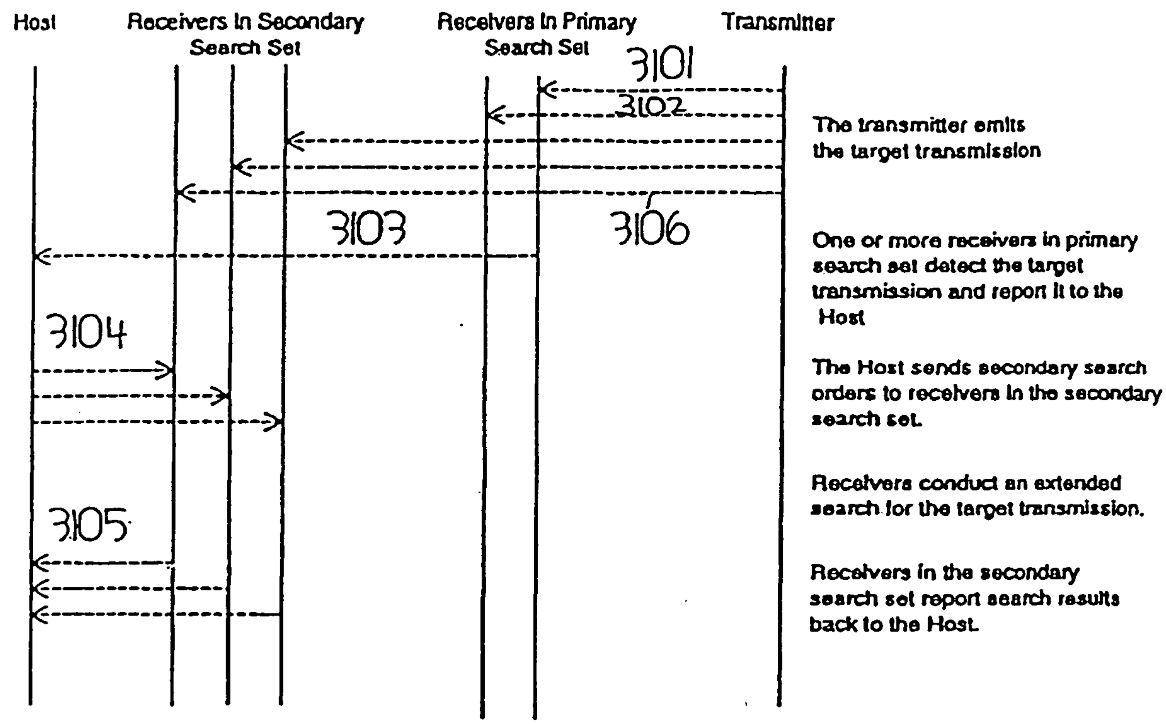

Host
Receivers In Secondary Search Set
Receivers In Primary Search Set
Transmitter
3101
3102
3103
3106
3104
3105
The transmitter emits the target transmission
One or more receivers in primary search set detect the target transmission and report it to the Host
The Host sends secondary search orders to receivers in the secondary search set.
Receivers conduct an extended search for the target transmission.
Receivers in the secondary search set report search results back to the Host.

FIGURE 31

INTERNATIONAL SEARCH REPORT

Interi nal Application No
PCT/CA 00/00492

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04Q7/38 G01S5/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01S H04Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 98 10307 A (DUPRAY DENNIS JAY ;KARR CHARLES L (US)) 12 March 1998 (1998-03-12)	1-3,5-9, 12,16, 20,22
Y	abstract; figures 5,8,10 page 52, line 14 -page 53, line 23 page 55, line 7 -page 57, line 8 page 60, line 33 -page 61, line 6 page 65, line 12 - line 30 page 91, line 10 -page 93, line 16 ---	4
Y	US 5 293 642 A (LO WING F) 8 March 1994 (1994-03-08)	4
A	abstract; figure 5 column 3, line 43 -column 4, line 4 column 6, line 65 -column 7, line 15 column 2, line 14 - line 36 ---	1
	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 September 2000	23. 10. 2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Niemeijer, R

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Interr nal Application No
PCT/CA 00/00492

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 892 278 A (FORSVARETS FORSKNINGS) 20 January 1999 (1999-01-20) the whole document	1
A	US 5 890 068 A (LACHAPELLE GERARD J ET AL) 30 March 1999 (1999-03-30) column 20, line 66 -column 21, line 42	1

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Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA 00/00492

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 26-114
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

Intern nal Application No

PCT/CA 00/00492

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9810307 A	12-03-1998	AU 4338597 A	26-03-1998
		AU 4479697 A	26-03-1998
		GB 2337386 A	17-11-1999
		WO 9810538 A	12-03-1998
US 5293642 A	08-03-1994	CA 2047253 A	20-06-1992
EP 0892278 A	20-01-1999	NO 973275 A	18-01-1999
US 5890068 A	30-03-1999	CA 2213979 A	03-04-1998

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box I.2

Claims Nos.: 26-114

In view of the large number and also the wording of the claims presently on file, which render it difficult, if not impossible, to determine the matter for which protection is sought, the present application fails to comply with the clarity and conciseness requirements of Article 6 PCT (see also Rule 6.1(a) PCT) to such an extent that a meaningful search is impossible.

Present claims 26-111 have a large number of independent claims relating to a wide variety of subjects, thereby rendering the nature of the invention for which protection is sought to be obscure.

Present claims 112,113 and 114 relate to a method and apparatus defined (inter alia) by reference to the following parameter(s): I, IA, IB,.........IVB and V. The use of these parameters in the present context is considered to lead to a lack of clarity within the meaning of Article 6 PCT. It is impossible to compare the parameters the applicant has chosen to employ with what is set out in the prior art. The lack of clarity is such as to render a meaningful complete search impossible.

Consequently, the search has been carried out for those parts of the application which do appear to be clear (and concise), namely the method for locating a transmitter using likelihood functions and estimated values of signal parameters as set out in present claims 1-25.

The applicant's attention is drawn to the fact that claims, or parts of claims, relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure.